101st Congress
1st Session

COMMITTEE PRINT

S. Prt.
101-26

AGRICULTURE, FORESTRY, AND GLOBAL CLIMATE CHANGE—A READER

PREPARED BY THE

CONGRESSIONAL RESEARCH SERVICE
LIBRARY OF CONGRESS

FOR THE

COMMITTEE ON
AGRICULTURE, NUTRITION, AND FORESTRY
UNITED STATES SENATE

APRIL 1989

Printed for the use of the
Committee on Agriculture, Nutrition, and Forestry

U.S. GOVERNMENT PRINTING OFFICE
95-674 WASHINGTON : 1989

5162-2

For sale by the Superintendent of Documents, Congressional Sales Office
U.S. Government Printing Office, Washington, DC 20402

COMMITTEE ON AGRICULTURE, NUTRITION, AND FORESTRY

PATRICK J. LEAHY, Vermont, *Chairman*

DAVID H. PRYOR, Arkansas
DAVID L. BOREN, Oklahoma
HOWELL HEFLIN, Alabama
TOM HARKIN, Iowa
KENT CONRAD, North Dakota
WYCHE FOWLER, Jr., Georgia
THOMAS A. DASCHLE, South Dakota
MAX BAUCUS, Montana
J. ROBERT KERREY, Nebraska

RICHARD G. LUGAR, Indiana
ROBERT DOLE, Kansas
JESSE HELMS, North Carolina
THAD COCHRAN, Mississippi
RUDY BOSCHWITZ, Minnesota
MITCH McCONNELL, Kentucky
CHRISTOPHER S. "KIT" BOND, Missouri
PETE WILSON, California
SLADE GORTON, Washington

Charles Riemenschneider, *Staff Director*
James M. Cubie, *Chief Counsel*
Christine Sarcone, *Chief Clerk*
Charles Conner, *Staff Director for the Minority*

FOREWORD

To: Members of the Committee on Agriculture, Nutrition, and Forestry

As concern over the possibility of future global climate change has crystallized in the past several months, a tremendous volume of material has been published seeking to explain the phenomena involved, discuss the likelihood that the world's climate will change, and predict the consequences of such changes on human society and its various activities. At my request, the Congressional Research Service has reviewed this vast outpouring of material and has selected a number of articles, book chapters, and other writings designed to provide, in one convenient compilation, samples of the best of current scientific thinking and interpretation, with a specific focus on the interests of our Committee.

In light of the importance of climate to the practice of agriculture and forestry, the Committee will of necessity spend a great deal of time in the next several years considering appropriate policy responses to both the threats and opportunities posed by future climate change. The purpose of this collection of pertinent writings is to keep before us some of the best thinking of the scientific and policy analysis communities on the subject.

Patrick J. Leahy,
Chairman, Committee on Agriculture,
Nutrition, and Forestry.

LETTER OF TRANSMITTAL

THE LIBRARY OF CONGRESS,
CONGRESSIONAL RESEARCH SERVICE,
Washington, DC, March 15, 1989.

Hon. PATRICK J. LEAHY,
Chairman, Committee on Agriculture, Nutrition, and Forestry, U.S. Senate, Washington, D.C.

DEAR MR. CHAIRMAN: I am submitting herewith a report entitled "Agriculture, Forestry, and Global Climate Change" which was prepared at your request. The report presents a number of selected writings on the probability of future climate change, its probable causes, how its effects might be distributed geographically around the world, and on potential impacts on the future practice of agriculture and forestry in the United States. Its authors have prepared brief introductions to the several sections of writings to help the Committee grasp quickly the scientific certainties and uncertainties associated with global climate change.

Preparation of this report was coordinated by David E. Gushee, Senior Specialist in Environmental Policy. Other contributors were John R. Justus, Specialist in Earth and Ocean Sciences; and Robert E. Morrison, Specialist in Ocean Science, of our Science Policy Research Division; and Jasper Womach, Specialist in Agriculture Policy; Susan R. Fletcher, Adela Backiel, and Jeffrey A. Zinn, Specialists in Natural Resources Policy, of our Environment and Natural Resources Policy Division.

The Service appreciates the willingness of the copyright holders to grant permission for the reprinting of these writings.

Sincerely,

JOSEPH E. ROSS, *Director.*

CONTENTS

Page

Foreword III

Letter of Transmittal V

OVERVIEW

Global Climate Change: The Science, Sources, Agricultural and Forestry Impacts, and Proposed Policy Responses, by David E. Gushee, Robert E. Morrison, and John R. Justus, Congressional Research Service 1

STATE OF THE SCIENCE

Introduction, by John R. Justus 24

Information on Selected Climate and Climate-Change Issues, by Harry F. Lins, Eric T. Sundquist, and Thomas A. Ager, U.S. Geological Survey. Open File Report 88-718 27

Scientific Basis for the Greenhouse Effect, by Gordon J. MacDonald. *Journal of Policy Analysis and Management,* vol. 7, No. 3, pp. 425-444 (1988) 58

The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment, by V. Ramanathan, *Science,* vol. 240, pp. 293-299, April 15, 1988 79

Cloud-Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment, by V. Ramanathan, R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmad, and D. Hartmann, *Science,* vol. 243, pp. 57-63, January 6, 1989 86

Unpleasant Surprises in the Greenhouse? by Wallace S. Broecker, *Nature,* vol. 328, pp. 123-126, July 9, 1987 93

The Need for Systems Research on Global Climate Change, by Fred B. Wood, Jr., *Systems Research,* vol. 5, No. 3, pp. 225-240 (1988) 97

Implications of Global Climate Change, by Sir Crispin Tickell. Keynote Address to Strategic Planning Seminar on the Long-Term Implications of Climatic Change. World Resources Institute, Jan. 5, 1988 113

Where Are We Headed in Responding to Climate Change? by John C. Topping, Jr., *International Environment Reporter,* pp. 555-561, October 1988 118

IMPACTS OF GLOBAL CLIMATE CHANGE ON AGRICULTURE

Introduction, by Jasper Womach, CRS 125

The Potential Effects of Global Climate Change on the United States. Chapter 10. Agriculture. Report to Congress October 1988. U.S. Environmental Protection Agency 128

Global Climate Change Holds Problems and Uncertainties for Agriculture, by Norman J. Rosenberg, Resources for the Future, in U.S. Agriculture in a Global Setting: An Agenda for the Future. National Center for Food and Agricultural Policy, Resources for the Future, pp. 203-218, 1988 180

Implications of a Global Climatic Warming for Agriculture: A Review and Appraisal, by B. Smit, L. Ludlow, and M. Brklacich, University of Guelph, in *Journal of Environmental Quality,* vol. 17, No. 4, pp. 519-527, October-December 1988 196

Assessing the Implications of Changes in Carbon Dioxide Concentrations and Climate for Agriculture in the United States, by Daniel J. Dudek, Environmental Defense Fund, in Preparing for Climate Change: Proceedings of the First North American Conference on Preparing for Climate Change. Climate Institute, pp. 428-450, October 1987 205

Page

Strategies for Adapting Agriculture to Adapt to Climate Change, by Stephen L. Rawlins, Director, Agricultural Systems Research Institute, in Preparing for Climate Change: Proceedings of the First North American Conference on Preparing for Climate Change. Climate Institute, pp. 451–459, October 1987 228

FORESTRY

Contributions of Forestry to Global Warming

Introduction, by Susan R. Fletcher, CRS 237

Global View of a Tropical Disaster, by Sandra Postel, Worldwatch Institute, in *American Forests,* pp. 25, 27–29, 69–71, November–December 1988 239

The Prospect of Solving the CO_2 Problem Through Global Reforestation, by Gregg Marland, Oak Ridge National Laboratory. Department of Energy Report DOE/NBB-0082, February 1988 246

A Green Fix to the Global Warm-Up, by Sandra Postel, Worldwatch Institute, World·Watch, pp. 29–36, September–October 1988 318

Vast Amazon Fires, Man-Made, Linked to Global Warming, by Marlise Simons. *New York Times,* pp. A1, A6, August 12, 1988 327

Ambitious Amazon Expedition Probes Forest's Role in Global Atmosphere, by Marlise Simons. *New York Times,* pp. C1, C9, June 2, 1987 329

The Significance of the Amazon Basin for Global Climatic Equilibrium, by Peter Bunyard. *The Ecologist,* vol. 17, No. 4/5, pp. 139–141, 1987 332

Government Policies and Deforestation in Brazil's Amazon Region, by Dennis J. Mahar, World Bank. Published by World Wildlife Fund and Conservation Foundation. 1989 335

Plan for Amazon Backed in Brazil, by Marlise Simons. *New York Times,* Section 1, p. 9, July 3, 1988 398

Impacts of Global Climate Change on Forests and Role of Forests in Mitigating Climate Change

Introduction, by Adela Backiel, CRS 399

The Potential Effects of Global Climate Change on the United States. Chapter 11. The Potential Impact of Rapid Climatic Change on Forests in the United States. Report to Congress. October 1988. U.S. Environmental Protection Agency 401

Rising Carbon Dioxide, Climate Change, and Forest Management: An Overview, by R. Sandenburgh, C. Taylor, and J.S. Hoffman, EPA, in The Greenhouse Effect, Climate Change, and U.S. Forests, W.E. Shands and J.S. Hoffman, Editors. The Conservation Foundation, 1987, pp. 113–121 440

Effects of Increasing Carbon Dioxide Concentration on the Physiology and Growth of Forest Trees, by P.J. Kramer and N. Sionit, in The Greenhouse Effect, Climate Change, and U.S. Forests, W.E. Shands and J.S. Hoffman, Editors. The Conservation Foundation, 1987, pp. 219–246 449

Prepared testimony of William R. Moomaw, World Resources Institute, before the Committee on Agriculture, Nutrition, and Forestry, December 1, 1988 477

Climate and Forests, by Roger A. Sedjo, Resources for the Future, and Allen M. Solomon, Oak Ridge National Laboratory. Presented to the Workshop on Controlling and Adapting to Greenhouse Warming sponsored by Resources for the Future, June 14–15, 1988 496

Climate Change and U.S. Forest Markets, by J.L. Regens and F.W. Cubbage, University of Georgia, and D.G. Hodges, U.S. Forest Service, in Preparing for Climate Change: Proceedings of the Second North American Conference on Preparing for Climate Change. Climate Institute. December 1988 543

IMPACTS OF GLOBAL CLIMATE CHANGE ON WATER RESOURCES

Introduction, by Jeffrey A. Zinn, CRS 550

Water Resources and Climate Change, by Kenneth D. Frederick, Resources for the Future, and Peter H. Gleick, University of California, Berkeley. Presented to the Workshop on Controlling and Adapting to Greenhouse Warming sponsored by Resources for the Future, June 14–15, 1988 552

Page

Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States, by Roger R. Revelle and Paul E. Waggoner, University of California at San Diego. In Changing Climate: Report of the Carbon Dioxide Assessment Panel, National Academy of Sciences. 1983......... 587

Water Resources Planning Under Climate Uncertainty, by J.R. Hanchey, K.E. Schilling, and E.Z. Stakhiv, U.S. Army Institute for Water Resources, Preparing for Climate Change: Proceedings of the First North American Conference on Preparing for Climate Change. Climate Institute. October 1987.... 601

CONSERVATION RESERVE PROGRAM

Opportunities and Limitations Associated With Using the Conservation Reserve Program (CRP), by Jeffrey A. Zinn, CRS........ 613

Congressional Research Service
The Library of Congress

Washington, D.C. 20540

GLOBAL CLIMATE CHANGE: THE SCIENCE, SOURCES, AGRICULTURAL AND FORESTRY IMPACTS, AND PROPOSED POLICY RESPONSES

A Briefing Paper

for

Committee on Agriculture, Nutrition, and Forestry

U. S. Senate

by

David E. Gushee
Senior Specialist in Environmental Policy

Robert E. Morrison
Specialist in Science Policy

John R. Justus
Specialist in Science Policy

November 21, 1988

CONTENTS

SUMMARY 1

WHAT IS THE GLOBAL CHANGE ISSUE? 2

RECENT ATMOSPHERIC EVENTS POSSIBLY RELATED TO GLOBAL WARMING . . . 3
  The Antarctic Ozone Hole 3
  Recent Episodes of Hot Weather 4
  The Drought of 1988. 4

WHAT DO THE MODELS TELL US? 4

COORDINATION AMONG INSTITUTIONS WORKING ON CLIMATE CHANGE 7

GREENHOUSE GASES: SOURCES AND TRENDS. 8
  Sources of Carbon Dioxide 9
  Sources of Methane 9
  Sources of Nitrous Oxide 11
  Sources of Halogenated Hydrocarbons 11
  Trends in Trace Gas Emissions and Concentrations 12

EFFECTS OF GLOBAL WARMING ON AGRICULTURE AND FORESTRY 14

PRIOR CONGRESSIONAL ACTIVITY. 16
  Climate and Effects Research 16
  Stratospheric Ozone Depletion 16
  Energy Efficiency 17
  Renewable Energy Sources 18
  Hydrogen and Fuel Cells as Energy Sources 19
  Nuclear and Fusion Power 10
  Abatement Technologies for Greenhouse Gas Emissions 20
  Alternate Fuels for Motor Vehicles 20
  Sustainable Economic Development 21

ACTIVITY IN THE 100TH CONGRESS 21

TABLES

  Table 1. Differences in Results Among Climate Models 6
  Table 2. Expected Relative Contributions to Global Warming (1980-2050) 8
  Table 3. Sources of Carbon Dioxide 9
  Table 4. Sources of Methane 10
  Table 5. Sources of Nitrous Oxide 11
  Table 6. Sources of Halogenated Hydrocarbons 11

FIGURES

  Figure 1. Carbon Dioxide Levels in Air Over Time 12
  Figure 2. Methane Levels in Air Over Time 13
  Figure 3. Future Carbon Dioxide Emissions 14

GLOBAL CLIMATE CHANGE: THE SCIENCE, SOURCES, AGRICULTURAL AND FORESTRY IMPACTS, AND PROPOSED POLICY RESPONSES

SUMMARY

Evidence is mounting that human activities are becoming sufficiently massive that they can affect the basic equilibrium processes of the Earth itself. With respect to the atmosphere, two such effects are of current policy interest. One is global climate change; the other is depletion of ozone levels in the stratosphere (treated in this report only to the extent to which it interacts with global climate change).

The Earth's temperature is regulated by a complex mix of chemicals and systems. The natural regulatory processes are not fully understood, but they include a key role for carbon dioxide (CO_2) and other naturally-occurring gases which are present in very small concentrations.

Humanity's burning of fossil fuels, coupled with its destruction of vast forests, has led over the past century to increases in CO_2 in the atmosphere to levels as high as, if not higher than, any ever inferred to have occurred from natural causes over the Earth's history. This increase in CO_2 levels may now be great enough to affect the Earth's processes of temperature regulation, with the net effect of increasing temperatures through a process similar to that in a greenhouse (light goes in, heat cannot get out fast enough, temperature goes up).

If such an effect has not yet occurred, it will probably do so within a few decades, according to current scientific thinking. The main reason: In the absence of policy intervention, worldwide fossil fuel use and forest destruction are expected to continue at ever-increasing rates for the foreseeable future.

Other gases, some natural and some man-made, also contribute to the greenhouse effect. Most notable are chlorofluorocarbons (CFCs), the same materials now indicted as causing stratospheric ozone depletion; methane generated from swamps, animal wastes, rice growing, and the like; and nitrous oxides, formed in combustion processes, lightning, and other events where air and very high temperatures combine.

Although climate change, if it occurs, is not expected to threaten the United States' ability to feed itself, it would affect crop yields, cause significant dislocations in regional agricultural economies, increase irrigation requirements, change livestock production system

requirements, and increase pest problems. It would cause northward shifts in tree species ranges, dieback along the southern edges of tree species ranges, and change tree growth rates, probably downward. Such effects on forestry could be apparent in 30 to 80 years, depending on the species, the soil, and the rate and extent of climate change.

Possible policy responses to the threat of global climate change include steps to reduce the rate of generation of greenhouse gases and quite different steps to prepare to cope with the effects of temperature increases should they occur. Congress has already begun to respond to the growing perception that global climate change is a possibility; its responses include an increased pace of research on both climate and on effects of climate change, and an increasing pressure on U.S. diplomacy to raise the issue in international discussions.

Many policies which affect either the rate of generation of greenhouse gases or the ability to respond to climate changes are already on the congressional agenda, but not for the purpose of responding to the global warming issue. Among these are energy efficiency improvements, alternative energy supplies, and environmentally sensitive development policies for both the developed and developing countries. With respect to agriculture and forestry, policy interest has been focused on coping with variations in "weather" from year to year, while "climate" has been assumed to be constant over the long term. Recently, attention has begun to focus on the potential for, and possible impacts of, changes in the climate itself.

The basic issue is whether the threat of global warming is real and, in light of uncertainties about the reality and the timing of that threat, how much of a policy response is appropriate at this time.

WHAT IS THE GLOBAL CLIMATE CHANGE ISSUE?

The Earth is unique among known planetary bodies. It has an atmosphere which not only contains the right amount of oxygen to sustain animal life, but which also contributes to a balancing of heat flows. Solar radiation comes into the atmosphere. Some is reflected back to space; some is absorbed by the atmosphere; the rest reaches the surface, where it is converted to heat. The heat reaching the surface, plus the heat generated by human activities, eventually works its way back up into the upper reaches of the atmosphere, where it gets radiated back into space. Overall, the amount of heat flowing back into space has to equal the amount of heat entering the atmosphere; otherwise, the Earth would either heat up or cool off, depending on whether less or more were reradiated to space.

The heat-balancing process going on in the atmosphere is affected by trace gases. Carbon dioxide (CO_2) is Mother Nature's primary actor in this regard, although other gases, some natural and others man-made (particularly methane, nitrous oxide, and chlorofluorocarbons (CFCs)), also play roles. Carbon dioxide has through geologic time also been involved in a balancing act; the amount generated by burning and by life processes (all animal life takes in oxygen (O_2) and gives off CO_2) equals over time the amount absorbed by plant life (plants take in CO_2 and give off oxygen), by water bodies, and by other mechanisms. Tremendous amounts of carbon are stored in fossil remains (including fossil fuels), in the oceans, and in rocks.

Since the beginning of the Industrial Revolution two centuries or so ago, the amount of CO_2 in the atmosphere has been increasing, the direct result of the increasing rate at which humanity has been burning fossil fuels. Burning coal, oil, gas, and wood at current rates releases more CO_2 than can be absorbed by the various absorption processes.

The amount of CO_2 in the stratosphere strongly affects the amount of heat energy transmitted back into space. The more CO_2, the less heat energy gets back out. The process works like a greenhouse; solar energy gets in but the heat cannot get out. CO_2 concentrations in the stratosphere are now about one-third higher than a century ago.

Atmospheric chemistry is much more complex than this simplified explanation. Many processes go on; other components present in small quantities also affect heat flows; the combination tends to buffer the effects of any one change so as to bring the system back to equilibrium. But the theory is that these buffering actions have only so much capacity. After a while, they can be gradually overridden and eventually overwhelmed.

Atmospheric scientists are claiming with ever increasing conviction that such an overriding, if not already here, is only a short time away. They estimate that greenhouse gas levels will double from pre-Industrial Revolution levels by some time between about 2025 and 2075 A.D. and estimate further that such a doubling would increase global average temperature by some amount between 3 and 16 degrees Fahrenheit (^{o}F). And, since the fossil fuel age would still be in full force, the outlook beyond the first doubling would be for even higher greenhouse gas emissions and continued further global warming for as long as fossil fuels dominate world energy supplies.

RECENT ATMOSPHERIC EVENTS POSSIBLY RELATED TO GLOBAL WARMING

Three recent developments on the meteorological front have together helped to focus public attention on the greenhouse phenomenon and the possibility that humanity has now become sufficiently numerous and active that its activities threaten the future ability of the atmosphere to sustain the natural balances. These are:

The Antarctic ozone "hole." The massive loss of ozone in the upper stratosphere was first evident in monitoring data in the mid-1970s but was not noted as a major phenomenon for several years. In the past 3 years, the "hole" has become much larger, lasted longer, and had widespread subsequent effects over at least most of the Southern Hemisphere. This year, the hole was smaller but still larger than in the early 1980s. Scientists now believe that they may have found the "smoking gun" causing the hole: decomposition products of CFCs absorbed into ice particles in the stratospheric cloud layer.

Recent episodes of hot weather. Four of the hottest years recorded in the past 100 years have occurred in the 1980s. The first 5 months of 1988 were the hottest yet (the rest of 1988, despite heat waves in the United States, has been somewhat cooler than normal).

The drought of 1988. Dry weather gripped the U.S. midsection, parts of the South, and parts of the Northwest this year. For some of the affected areas, this was the second or third year of unusually low rainfall.

James E. Hansen, director of NASA's Institute for Space Studies was the first scientist to claim that global warming is already here, that the heat is its messenger, and that the drought is consistent with predictions in some of the major climate models (this was before the Senate Committee on Energy and Natural Resources on June 23, 1988). Since then several others, including Gordon MacDonald, chief scientist of the Mitre Corp., and John Firor, director of advanced study programs for the National Center for Atmospheric Research, have also come forth with the same conclusion. Most other atmospheric scientists agree that these patterns are consistent with but do not yet prove the theories which underlie predictions that global warming will be the result of continued and increasing release of greenhouse gases.

WHAT DO THE MODELS TELL US?

Numerical climate models have been used extensively in recent years to study climatic changes which could occur from changes in environmental variables. Both simple models and the more complex three-dimensional global circulation models (GCMs) show a global warming with increased concentrations of carbon dioxide and other radiative trace gases in the atmosphere.

A convenient measure of increased carbon dioxide concentration, which has been used for discussion purposes and for climate change predictions is the doubling of the present concentration of atmospheric carbon dioxide. Since carbon dioxide is the preponderant variable "greenhouse gas" in the atmosphere, and the radiative effects of the "greenhouse gases" are generally additive, the effect of increasing the concentrations of the other trace gases is simply accommodated in the prediction models by assuming their increases to be part of the carbon dioxide doubling.

Estimated warming due to intensified greenhouse effect varies with latitude, being greatest toward the poles and least near the Equator. It is also greater in the Northern Hemisphere than in the Southern Hemisphere, because of the greater expanses of ocean surface south of the Equator, leading to greater heat absorption at the Earth's surface. Increased warming is also expected to be greater for a given region, other things being equal, in winter than in summer.

General circulation models (GCMs) have been used in a number of "climate model experiments," where there is an attempt to quantify differences between model run results for existing conditions and model predictions obtained after changing significant model inputs, such as a doubling of atmospheric carbon dioxide. Such experiments are also called sensitivity analyses. Before models are used in such experiments, their development and refinement has included many "runs" and re-calibrations until they are validated, so that they can "predict" (or reproduce) with reasonable accuracy current (or control) climatic conditions, using pertinent current data as input and appropriate initial and boundary conditions.

Although numerical models tend to give reasonable and consistent results on a global or hemispherical basis, the state of model development is such that precision is reduced for smaller regions. Consequently, estimates of increased greenhouse warming on a regional basis from different models show considerable variability, with uncertainties and inconsistencies increasing as geographical dimensions decrease.

Predicted temperature increases from carbon dioxide doubling, for winter and summer, and for the entire globe and progressively diminishing regions (Northern Hemisphere, contiguous United States, and midwestern United States), derived from each of these models were compared in a recent study by Stanley L. Grotch at Lawrence Livermore National Laboratory for the U.S. Department of Energy.[1] Results of this intercomparison are summarized in Table 1. They show clearly how the results differ among models as the geographical area being treated changes.

The four general circulation climate models (GCM) whose results were compared by Grotch in his study, listed in Table 1 by acronym, are identified by name and by research institution below: [2]

CCM - Community Climate Model developed at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. (There are a number of versions of the CCM, each with somewhat different capabilities and provisions)

---

[1] Stanley L. Grotch. Regional Intercomparison of General Circulation Model Predictions and Historical Climate Data. Prepared for the U.S. Department of Energy, Office of Energy Research, DOE/NBB/0084. (Prepared under contract No.. W-7405-ENG-48.) April 1988. 309 p.

[2] Ibid. p. 3.

GFDL - Climate model developed by the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration, in Princeton, New Jersey.

GISS - Model developed at the Goddard Institute for Space Sciences, National Aeronautics and Space Administration, Greenbelt, Maryland.

OSU - Model developed at Oregon State University, Corvallis, Oregon.

TABLE 1

Median changes in surface air temperature (in degrees Centigrade) for a doubling of the carbon dioxide concentration, as predicted by four general circulation models (GCM) for four geographical domains and two seasons. [3]

	Domain of Comparison			
VARIABLE AND MODEL	GLOBAL	NORTHERN HEMISPHERE	CONTIGUOUS U.S.	MIDWESTERN U.S.
	December-January-February			
Increases in Median Temperatures from doubling carbon dioxide (degrees Centigrade)				
CCM	3.72	3.74	3.10	3.32
GFDL	4.50	5.65	4.76	5.04
GISS	4.64	5.58	5.14	5.57
OSU	3.19	3.12	3.35	3.54
	June-July-August			
Increases in Median Temperatures from doubling carbon dioxide (degrees Centigrade)				
CCM	3.30	2.85	2.99	3.36
GFDL	4.06	5.64	6.49	6.65
GISS	4.33	3.35	3.71	3.80
OSU	3.03	3.33	3.56	3.64

---

[3] Adapted from U.S. Department of Energy, Office of Basic Energy Sciences. Research Project of the Month. June 1988. Based on study by Grotch. Op. Cit.

COORDINATION AMONG INSTITUTIONS WORKING ON CLIMATE CHANGE ISSUES

There is now a persuasive view held by the scientific community and the Federal science agencies that earth science and atmospheric change activities, would benefit if those activities, Federal and national, were conducted with a greater emphasis on coordination and cooperation. Capitalizing on this view and the momentum generated by the newly organized International Geosphere-Biosphere Program (IGBP), the National Academy of Sciences Committee on Global Change (CGC) [also known as the U.S. National Committee for the IGBP], the National Climate Program Office, the President's Office of Science and Technology Policy, the Office of Management and Budget, and the 10-member Interagency Coordinating Committee on Earth Sciences, recently established in the Federal Coordinating Council for Science, Engineering, and Technology, are currently reviewing agency budget priorities and scientific infrastructure requirements.

Although one or two budget planning cycles might be required before any formal policy could prescribe a specific, coherent approach and overall funding level, such an evolution would allow the various agencies, in cooperation with the scientific community and the Academy Committee on Global Change to define a fiscally realistic and scientifically sound Climate and Global Change Program. Such a program would likely consist of enhancements of existing programs in earth system science and in climatic change and variability plus some new starts as well as some program terminations.

Certain initiatives have already been incorporated into this evolving program definition, including those of the National Research Council (reported in Global Change in the Geosphere-Biosphere: Initial Priorities for an IGBP, 1986), the National Aeronautics and Space Administration (Earth System Science Overview: A Program To Study Global Change, 1986), the National Science Foundation (Global Geosciences Initiative, started in FY87 with enhancements of existing programs plus some new starts), the National Oceanic and Atmospheric Administration (Climate and Global Change Initiative, begun in FY88 with enhancement of existing programs), and the National Climate Program Office and Interagency Climate Program Policy Board (reported in National Climate Program Five-Year Plan, 1988-1992).

The "Global Climate Protection Act of 1987", (Title XI, P.L. 100-204), delegates responsibility to the President through the Environmental Protection Agency for developing and proposing to Congress, a coordinated national policy on global climate change. This policy is to consider findings of the Interagency Committee on Earth Sciences, the National Academy of Sciences, the National Oceanic and Atmospheric Administration, the National Climate Program Office, the National Aeronautic and Space Administration, the Department of Energy, the Environmental Protection Agency, and other organizations in the conduct of research. The Domestic Policy Council is the coordinating vehicle for Federal agencies participating with EPA to carry out P.L. 100-204 mandates. The Act encourages coordination of domestic and international climate activities with research and impact analyses that are consistent with policy goals.

Other current EPA efforts on global climate change have been stimulated both by Congressional action and its own independent work through the Office of Research and Development. Pursuant to a Congressional request made in 1986, EPA will report by the end of 1988 on (1) health and environmental effects of climate change on agriculture, forests, water resources, human health and other aspects of the environment in four geographic regions of the nation; and (2) policy options for stabilization and eventual reduction of greenhouse emissions resulting from energy use, CFC production, deforestation, and other activities not only domestically but also worldwide. EPA has coordinated with the National Climate Program Office and actively sought participation of other federal agencies and the broader scientific community in the research process leading up to these reports.

GREENHOUSE GASES: SOURCES AND TRENDS

The four most important greenhouse gases, according to current scientific thinking,[4] are carbon dioxide, methane (major constituent of natural gas), nitrous oxide, and chlorofluorocarbons. How important each is projected to be over the 70 years is summarized in Table 2.

TABLE 2

Expected Relative Contributions
to Global Warming
(1980-2050)

Gas	Relative Contribution
Carbon Dioxide	47%
Methane	14
Nitrous Oxide	10
CFC-11	10
CFC-12	19
Halons	Small

These relative contributions to global warming are not exact. They are estimates based on many assumptions, among which are estimates of population growth, economic growth, future patterns of energy use, agricultural practices, and the effectiveness of the Montreal Protocol on CFCs. The major conclusion to be drawn from the table is that, although carbon dioxide is the most ubiquitous greenhouse gas, it will contribute half or less of the total global warming capacity generated by human activities through the middle of the next century. Thus, policy responses must consider actions affecting emissions of the other greenhouse gases as well as actions against growth of CO_2 emissions.

---

[4] Information on greenhouse gases summarized in the next several tables is taken from "A Primer on Greenhouse Gases," Department of Energy Report DOE NBB0083, March 1988.

Sources of Carbon Dioxide

The amount of carbon dioxide naturally cycling through the biosphere is enormous (see Table 3). It dwarfs the amount being generated by human activity. Yet the naturally cycling CO_2 has been kept in balance between generation and absorption by various processes on the Earth such as vegetation, animal life, and absorption and desorption by water. Human activities over the past two centuries have, it is now believed, grown large enough to affect this balance.

TABLE 3

Sources of Carbon Dioxide
(Millions of Tons of Carbon per Year)

Source	Amount	Uncertainty
Natural		
Oceans		
Gross Annual Release	104,600	1,900
Land		
Gross Annual Release	64,000	55,000
Man-Made		
Fossil Fuel Use	5,000	500
Land Use Conversion	1,300	1,300

Generation by natural sources and absorption by natural sources are in approximate balance over time, as evidenced by the historic data on CO_2 levels in the atmosphere and the stability of climate over time. The fact that scientists do not have a precise knowledge of all the sources and sinks for carbon in the biosphere (the carbon cycle) is reflected in the uncertainty numbers.

Sources of Methane

Methane in the atmosphere is coming from both natural and man-made sources, as summarized in Table 4.

TABLE 4

Sources of Methane
(millions of Tons of Methane Per Year)

Source	Amount	Uncertainty[5]	Share[5]	Range[5]
Natural				
Wild Animals	5	3	1%	0-2%
Wetlands	110	50	22%	12-33%
Lakes	4	2	1%	0-1%
Tundra	3	2	1%	0-1%
Oceans	10	3	2%	1-3%
Termites	25	20	5%	1-9%
Other	40	40	8%	0-16%
Subtotal	197	120	40%	
Man-Made				
Cattle	75	35	15%	8-22%
Rice	70	30	14%	8-20%
Biomass Burning	70	40	14%	6-22%
Natural Gas Production	50	25	10%	5-15%
Solid Waste	30	30	6%	0-12%
Subtotal	295	160	60%	
Total	492	280		

Scientific understanding of the facts about methane generation and absorption is rather incomplete, as reflected by the high proportion of uncertainties which are half or more of the magnitude of the estimates. The impact of these uncertainties on global climate change is magnified, because methane is more absorptive of heat than CO_2 is by perhaps as much as 20 times.

---

[5] For Tables 4 through 7, "Uncertainty" is an estimate of the possible error in the estimate tabulated under "Amount." "Share" is the relative importance of the source compared to all sources. "Range" is the lower and upper limits of the "Share" taking "Uncertainty" into account. For example, the best current guess for the relative contribution of wetlands to overall methane generation is 22% but, because of uncertainties in measurements of each source and the possibility that not all sources have been identified, wetlands share might be as low as 12%. On the other hand, it might be much higher than 22%, perhaps as high as 33%, either because the estimate for its contribution of methane emissions might be too low or because the estimates of other sources might be too high. Further, even these ranges are subject to revision as new data are generated, since they are set on the basis of estimates of the errors and not on precise knowledge of the errors.

Sources of Nitrous Oxides

Nitrous oxide is not a well-characterized trace component in the atmosphere, nor are its natural sources and sinks well understood. The same can be said of man-made sources. As a result, the uncertainties are large fractions of the estimates, and the ranges are large in percentage terms.

TABLE 5

Sources of Nitrous Oxides
(Millions of Tons of Nitrogen Per Year)

Source	Amount	Uncertainty	Share	Range
Natural				
Oceans	2	1	13%	6-20%
Soils	7	4	43%	20-70%
Subtotal	9	5	56%	
Man-Made				
Fossil Fuels	4	1	25%	20-30%
Burning Biomass	0.7	0.2	4%	3-6%
Fertilized Soils	0.8	0.2	5%	4-6%
Cultivated Natural Soils	1.5	0.5	9%	6-13%
Subtotal	7	1.9		
Total	16	6.9		

Sources of Halogenated Hydrocarbons

The halogenated hydrocarbons do not exist in nature. They are used primarily for air conditioning fluids, as blowing agents for plastic foams, and as cleaning solvents for the very exacting cleansing requirements of modern electronic parts. Uses as aerosol propellants have been phased out in a few countries, including the United States, but in most of the world, that use is responsible for about one fourth of total consumption

TABLE 6

Sources of Halogenated Hydrocarbons
(Millions of Tons Per Year)

Source		Amount	Uncertainty
Natural		None	
Man-Made			
	CFC-11	0.33	0.05
	CFC-12	0.44	0.05
	Halons	0.01	Small
	Total	0.78	0.10

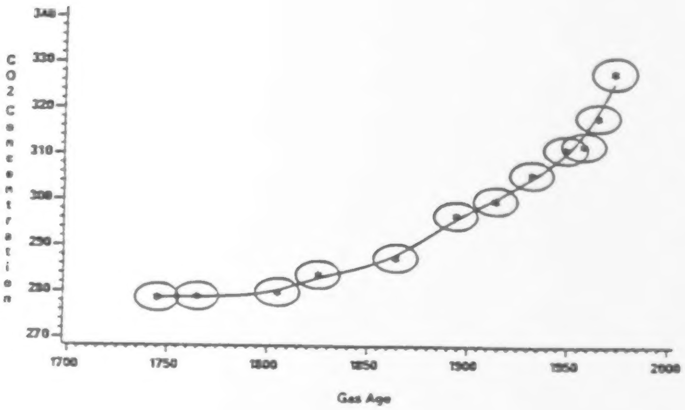
Trends in Greenhouse Gas Emissions and Concentrations

From these tables of data, it can be seen that, aside from CFCs which have no natural sources, man-made emissions of greenhouse gases, although large, are not the only, or even perhaps the largest, source of these materials. The concern about man-made emissions is based not only on current levels, which may or may not be causing climate change at this time, but on increase in emission rates from human activities and increases in concentrations of these gases in the atmosphere. Scientific thinking is almost in full agreement that sooner or later these increases, if continued, will cause unprecedented global climatic effects.

Figure 1 shows how carbon dioxide concentrations of the atmosphere have been increasing over the past two centuries. The data come from ice samples and from (most recently) air sampling on top of Mauna Loa volcano in Hawaii.

FIGURE 1

Carbon Dioxide Levels in Air Over Time

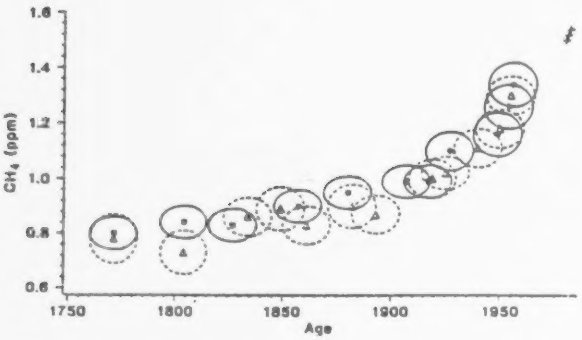


Source: National Climate Program Annual Report 1985

Figure 2 shows a similar story for methane. These data are also taken from ice samples of various ages and from recent atmospheric measurements.

FIGURE 2

Methane Levels in Air Over Time



Source: Stauffer, et al. Science, 27 Sept., 1985, p. 1386.

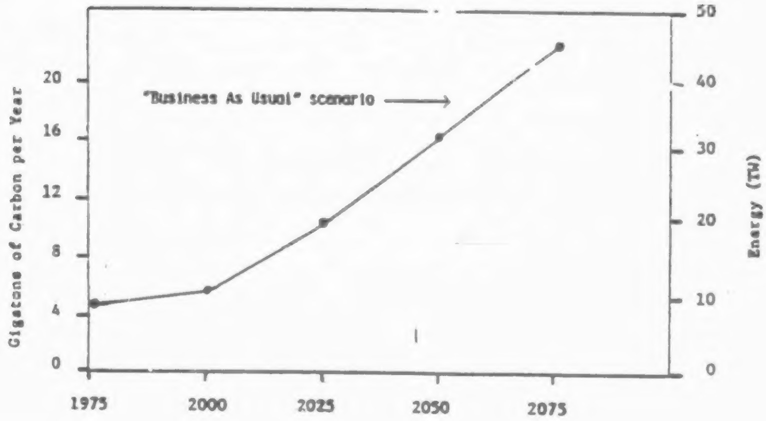
These graphs have the shape known technically as "logarithmic curves," which means that the concentrations are increasing at a constant annual percentage, which means an increasing amount each year. The shapes are the same for nitrous oxide and for the halogenated hydrocarbons.

These changes in atmospheric concentrations reflect changes in the rates in tons per year at which the gases are being emitted. These emission rates, too, if graphed, would have the same shape as Figures 1 and 2. Extended into the future, they would look like Figure 3, which shows a "business as usual" projection of CO_2 emissions rising in the same logarithmic fashion.

It is the logarithmic growth of emissions of greenhouse gases, the likelihood that this growth will continue, and the inexorable resulting increase in concentrations of greenhouse gases in the atmosphere--much more than the recent spate of hot weather and drought--which underlies the deep concern of the scientific community concerning the future well-being of the planet.

FIGURE 3

Future Carbon Dioxide Emissions



Source: Taken from testimony of Michael Oppenheimer, Environmental Defense Fund, to Senate Committee on Energy and Natural Resources, June 23, 1988, and printed in S. Hrg. 100-461, Part 2, p. 90.

EFFECTS OF GLOBAL WARMING ON AGRICULTURE AND FORESTRY

Despite technological advances over the past half century, weather is still a crucial factor in agricultural productivity. As EPA's current study points out,[6] the 1988 drought in the U.S. east and midwest will decrease corn yields by about 40%.[7] Future changes in climate from global warming would thus be expected to have significant impacts.

EPA in preparing to write its draft report commissioned more than a dozen studies to look into, among other factors, the impacts of prospective climate change on pests, technological needs, and regional impacts. It modeled crop responses, factored in changes in soil and water avalability, and estimated economic consequences and potential changes in land use and irrigated acreage.

---

[6] "The Potential Effects of Global Climate Change on the United States," Draft Report to Congress, Environmental Protection Agency, October 1988.

[7] Latest estimates from U. S. Department of Agriculture are closer to 30%.

With respect to U.S. crop yields, the Agency found:

. Climate change alone would probably decrease average yields of corn, soybeans, and wheat, except in the northern-most growing regions.

. Increasing CO_2 levels in the air, coupled with other changes, could overcome[8] the negative effects of climate change alone in some areas. Whether these modeling results would actually occur is not certain.

. Yield stabilities might decrease, given the probability of more days of extreme heat.

With respect to other impacts, the Agency found:

. Although U.S. production would probably continue to meet domestic needs, there would be a small to moderate decrease in agricultural output.

. Since the study did not examine the rest of the world, the impact of reduced total output on exports, global food supplies, or the U.S. trade balance was not estimated.

. There would be changes in regional agricultural practices, the impacts of which would be negative in some areas as those crops currently produced there became less suitable as climate changed. In other areas, probably to the north, such changes might be positive, provided the soils and moisture availability were also favorable.

. The demand for irrigated acreage would probably increase.

. Temperature increases may enhance the survival over winter of some insect pests, extend their northward ranges, increase pest species with more than one generation per year, and allow pest establishment earlier in the growing season.

. Farmers may adjust by changing crop species and farming practices, irrigating more, using more pesticides, and harvesting earlier. Whether these adjustments will suffice will depend on the severity of the climate change.

---

[8] There is some evidence that growth rates increase as CO_2 content in the air over plants increases, other factors being equal. However, these results are from controlled experiments, and the effects of wind, rainfall, and other variables have not been measured.

With respect to forestry, the EPA found:

. The northern and southern boundaries of the growing range for many forest species might move northward by up to 600 miles.

. If climatic change is too fast, some species might not be able to form healthy seeds, thus halting migration.

. Forest productivity might decline by 50 to 100% along the southern boundaries of the growing range, but productivity might increase along the northern limits as slower-growing trees would be replaced by faster-growing ones.

. Changes in climate, when added to the multiplicity of stresses many forested areas are currently undergoing, might produce major regional disturbances such as fires, disease outbreaks, wind damage, and reduced productivity.

PRIOR CONGRESSIONAL ACTIVITY

Congress has had on its agenda for many years at least nine policy threads which together make up much of the fabric of legislative action to reduce the rate of, if not to prevent, global climate change.

Climate and Effects Research

In 1978, Congress enacted the National Climate Program Act, P.L. 95-367, setting up a multi-year, multi-agency climate research program designed to improve climate knowledge and to make useful climate information more widely available. This program was recently reviewed by the Congressional Research Service (CRS Report 88-289, The National Climate Program: Background and Implementation, by John R. Justus, Mar. 31, 1988). One major aspect of this program is research related to the greenhouse effect and possible global warming. President Reagan transmitted a report to Congress in January 1988 summarizing Federal Government activities related to the greenhouse effect; this is reprinted as Appendix V of CRS Report 88-289. The 100th Congress enacted the Global Climate Protection Act (Title XI of P.L. 100-204), discussed earlier in this report (page 7).

Stratospheric Ozone Depletion

In 1973, two research scientists, Rowland and Molina, published a chemical theory implicating fully halogenated hydrocarbons (CFCs) in chemical reactions which would lead to depletion of the ozone levels in the stratosphere. Even though the theory was not fully demonstrated experimentally and measurements of ozone concentrations in the stratosphere did not show measurable depletion, Congress included in its amendments to the Clean Air Act in 1977 instructions to EPA to "conduct a study of the cumulative effect of all substances, practices, processes, and activities which may affect the stratosphere, especially ozone in the stratosphere" (Section 153, Clean Air Act, as amended).

Since then, CFCs were banned in aerosols in 1978 by EPA and FDA, and the United States has entered into two major international agreements -- The Convention for the Protection of the Ozone Layer, ratified by the United States in 1986, and as a part of that Convention, the Montreal Protocol on Substances that Deplete the Ozone Layer, ratified by the United States in March 1988. The Protocol will enter into force in 1989 if enough countries have ratified it by then. (Ratification by the European Common Market is all that remains necessary for entry into force; it is expected by mid-December.)

Institutional processes for reacting to the possibility of stratospheric ozone depletion -- cooperation in research both domestically and internationally, plus diplomatic initiatives within the United Nations and through other international channels -- have been remarkably successful. This success is the more notable given the scientific uncertainties which dominated the debate until very recently.

These successes have led to many suggestions that the same institutional and diplomatic methods should be applicable to the greenhouse problem as well. Two recent international convocations have picked up on this theme. The International Conference on the Changing Atmosphere, held in Toronto, Canada, June 27-30, 1988, was sponsored by the Canadian government, United Nations Environmental Program (UNEP, central to the success of the ozone depletion agreements), and the World Meteorological Organization. Delegates represented 46 countries, 15 international organizations, and 47 environmental groups. Delegates from 35 countries convened November 9-11, 1988, in Geneva, Switzerland, for the first meeting of the newly-established Intergovernmental Panel on Climate Change (IPCC). Also under the auspices of UNEP and WMO, the IPCC will, over the next 18 months, coordinate an international scientific assessment of the magnitude, timing, potential impacts, and possible response strategies to global warming. The U.K. delegation leads a working group analyzing the state of the science; the U.S.S.R. delegation leads a working group analyzing the environmental, economic, and social impacts of climatic change; and the U.S. delegation leads a working group analyzing response strategies.

Energy Efficiency

Energy conservation became a major subject of congressional policy interest in the 1970s after the Arab oil embargo. An extensive R&D program was created within the Department of Energy (DOE). Upon the change in Administrations in 1981, a tug of war developed between Congress and the executive branch, with the latter proposing drastic cuts amounting to phase-out of Government presence in conservation R&D and Congress putting money back in but at much lower levels than in the 1970s.

It is interesting to note that this tussle, which has lasted almost a decade, has been carried out almost completely in either an energy policy context or an economic policy context, but not in a global warming context. That is, efficiency in oil use has been recognized as important to reduce dependence on imported oil, while efficiency in electricity use has been viewed as important to reduce the need for expensive additional electricity generating capacity. The political issue has been the appropriate governmental role.

Most analyses of future energy demand indicate that world oil, gas, and coal use will continue to increase as far ahead as the analysts can see, despite new technological contributions to energy efficiency. Such projections result from assumptions about future rates of population growth and increases in energy use in developing nations. Translated into the "greenhouse" context, these studies lead to estimates of CO_2 concentration in the atmosphere doubling by anywhere from 2025 to 2075 A.D. Increases in the other greenhouse gases would be additive to the warming effects of the CO_2 increases.

Several groups have been examining the potential for concerted policy thrusts to push improvements in energy efficiency beyond the rate of their "natural" acceptance driven by market forces in order to slow the rate of increase of energy demand and therefore CO_2 emissions. A Department of Energy study of such studies, released in draft form by Sen. Leahy (Dem.-Vt.) in early November,[9] concludes that U.S. CO_2 emissions, expected to rise about 38% in theperiod to 2010, could be held to current levels only by explicit policy interventions, mostly in the area of electricity demand. To reduce U.S. CO_2 emissions significantly below current levels "would require aggressive policy intervention" such as increased gasoline prices, auto fuel economy standards, and substitution of natural gas for oil and coal.

Renewable Energy Sources

Renewable energy (by which is usually meant solar, water, and wind power, and biomass use) has been supported by Congress as part of its alternative energy R&D program assigned to DOE. Its justification has been primarily on the basis of reduction of oil import dependence, anticipation of oil and gas resource depletion, and reduction of air pollution from sulfur and nitrogen oxides. DOE's renewable energy program has been focused on solar energy for space heating and cooling and for direct generation of electricity, wind power for electricity generation, and biomass use primarily for ethanol and methanol production. These technologies generate electricity without using fossil energy, avoid using electricity or fossil energy for space heating, water heating, and process heat, and substitute renewable fuels for fossil fuels. All such substitutions reduce CO_2 generation.

---

[9] "An Analysis of U.S. CO_2 Emissions Reduction Potential in the Period to 2010," by J. A. Edmonds, W. B. Ashton, H. C. Cheng, and M. Steinberg, prepared for the Department of Energy. Draft dated Sept. 30, 1988.

The history of these R&D initiatives over the past decade is similar to that of energy efficiency R&D: Large programs were mounted in the mid-1970s in response to the Arab oil embargo and its attendant oil price rise, but the Reagan Administration's view of the appropriate role for the Federal Government, plus the somewhat discouraging results from the earlier governmental effort and the Federal budget situation, have combined to limit the scale of these programs in the 1980s.

Hydrogen and Fuel Cells as Energy Sources

For perhaps half a century, suggestions have been made that the ultimate fuel would be hydrogen produced from water, probably ocean water. There would be no emitted ozone precursors, carbon monoxide, carbon dioxide, or sulfur oxides; no ash to dispose of; no large earth-moving or drilling operations associated with resource extraction. But there must be a cheap, clean energy source to split apart the water molecules to free the hydrogen contained in them.

Over the years, solar, nuclear, and fusion energy have been proposed as the source of the needed input energy. Congress has been supporting R&D on all of these both for their own values and for their potential as inputs to a future hydrogen fuel system. Congress has also funded research on other technical issues associated with large-scale hydrogen use, such as transportation and storage (hydrogen tends to embrittle metals) and engines. Major hurdles remain to be cleared before this technology becomes available for significant application.

Fuel cells represent, however, a nearer-term option. Fuel cells convert chemical energy directly into electricity, usually by combining hydrogen and oxygen. There are many different ways to generate the hydrogen in the cell, and the Department of Energy has had a program for about 20 years. NASA also has a program. Both have had funding battles over the years similar to those of energy efficiency and alternative funds.

Nuclear and Fusion Power

The fact that producing electricity from nuclear power does not produce CO_2 emissions so far has not had much effect on the ongoing national and international debates over the future role of this energy source. The growing pressure from the environmental community on greenhouse gases as an international problem of increasing criticality will lead to increasing recognition that nuclear power has this attribute.

Scientists, policy analysts, and environmentalists are cautious, to say the least, about the possible future role of nuclear energy as a strategy to mitigate CO_2 emissions. Among the concerns expressed are plant operating safety and ultimate disposal of radioactive wastes. Even if these concerns were expeditiously resolved, lead times required for nuclear facility planning and construction would prevent nuclear from having much of an impact on CO_2 emissions within the 2010 time frame.

Fusion energy is currently a research topic. It will not be a viable option for at least a quarter of a century. Congress has been supporting research at a healthy level and has been supportive of international cooperative research as well.

Abatement Technologies for Greenhouse Gas Emissions

Carbon dioxide is a commercial product, as well as a greenhouse gas. As a commercial product, technologies have been developed for its production and use. Major uses are as a refrigerant, an agent for enhanced recovery of oil from older wells, a chemical intermediate, and a fire suppressant.

A number of processes for removal of CO_2 from gas streams are currently in use. Most are based on scrubbing the CO_2-laden gas with some sort of absorbent or reactant, either liquid or solid. Diffusion across semipermeable membranes and thermodynamic processes are also used.

However, the current market for CO_2 is small compared to the amount of CO_2 which would be recovered if abatement were to be widely practiced. The technologies now in use were not developed for purposes of emission reduction, are exceedingly expensive and energy-consuming, and would not be attractive economically were CO_2 recovery required at levels beyond the ability of society to use the recovered CO_2.

Alternate Fuels for Motor Vehicles

Motor vehicle emissions relate to the greenhouse effect through two avenues: their fuels generate CO_2 when burned; their other emissions (unburned fuel, partially oxidized hydrocarbons, carbon monoxide, and nitrogen oxides) combine to form ozone in the troposphere, a phenomenon which intensifies as ambient temperatures increase (as they would under global warming). In addition, among fuels alternative to gasoline being fostered for one or more of a variety of reasons is methanol. One of the reasons for support of methanol is its potential for reducing emissions of pollutants which lead to urban ozone formation. Another reason is its potential for ultimate manufacture from a domestic raw material, coal. Yet, given current technologies, making methanol from coal sharply increases -- perhaps even doubles -- net CO_2 production per mile driven.

Thus, methanol is caught on the horns of what some see as a dilemma. Making it from coal for energy policy reasons would seem to work against any program for reduction of greenhouse gas emissions. On the other hand, methanol, like ethanol, can be made from biomass, which would appear to offer some potential for reductions in net CO_2 emissions over the long term.

However, both of these products made from biomass are net energy consumers, given current technologies and forecasts for their improvement.

Sustainable Economic Development

Concern about the environmental impact of many types of economic development projects in the Third World has been voiced consistently since the Stockholm Conference of 1972. Among the bases for this concern, with respect to greenhouse, are forest destruction, which reduces the Earth's uptake of CO_2 from the atmosphere, and inefficient use of fossil fuels for industrial purposes and electricity generation, which increases CO_2 emissions.

This concern has been expressed through American representatives in several United Nations organizations, the multilateral lending agencies such as the World Bank and the International Monetary Fund (IMF), and in the philosophies underlying U.S. agencies' international aid programs, by the Agency for International Development (AID) and the U.S. Department of Agriculture (USDA) in particular. There is recent evidence that, at least in some developing countries, officials recognize the validity of such environmental concerns and no longer see them as part of a policy to retard Third World development or as luxuries of importance only to wealthy nations.

ACTIVITY IN THE 100TH CONGRESS

The summer-1988 streak of hot weather, coupled with other developments described earlier, has precipitated the introduction of several multi-faceted bills designed to address the greenhouse issue. The first two such bills, S. 2663 (Stafford et al.) and S. 2667 (Wirth et al.) were introduced in late July 1988. S. 2663 is basically a regulatory approach and would control CFCs, emissions of CO_2, and methane. In addition, it would regulate ozone precursors and carbon monoxide using the approaches of S. 1894, Titles I and III. S. 2667 is basically an energy policy bill, focusing on efficiency in energy production and uses; accelerated development and deployment of renewable energy technologies, advanced nuclear reactors, and fusion; and adding the proposed technology's impact on net CO_2 emissions as an evaluation criterion under the Department of Energy's Clean Coal Technology Program. Both bills would increase R&D funding and call for improved forms of international cooperation. H. R. 5380 and H. R. 5460 in the House take approaches similar to that of S. 2667.

The 100th Congress considered modifying ongoing climate research planning by assigning the lead role for developing and coordinating a National Global Change Research Plan to the Federal Coordinating Council for Science, Engineering, and Technology (S. 2614). The bill was reported from committee but did not receive floor action. It also considered requesting the President to establish a cooperative international research program (S.Con.Res. 5), but this proposal was not reported from committee.

STATE OF THE SCIENCE

(By John R. Justus, Specialist in Earth and Ocean Sciences and Robert E. Morrison, Specialist in Marine Science)

Several environmental problems are now recognized to be global. The importance of one problem in particular has been underscored by a growing consensus of climate and atmospheric scientists in academia, government, and international scientific organizations. These scientists have discovered that global changes in Earth's climate and biosphere might be induced by increasing concentrations of certain gases in the atmosphere. Some of these gases are natural constituents of the atmosphere, others are man-made, but the essence of the problem is that their increasing concentrations can alter the chemical balance or the heat budget of the atmosphere. According to current projections, such alterations may potentially lead to a warmer climate, portending a potpourri of beneficial and adverse effects for human health and welfare and for the land and aquatic biospheres. By studying the results of computer models of atmospheric chemistry and dynamics, as well as observing Earth's climatic history, agreement is emerging among international scientists who acknowledge that, although long-term atmospheric change may be subject to some degree of control, some potentially disruptive atmospheric and ecological changes in the coming decades may be unavoidable.

There are varying opinions on the timing and magnitude, but most scientists concur that carbon dioxide (CO_2) released from combustion of wood, oil, gas, and coal, as well as from forests and soils because of certain land use practices, might alter the Earth's environment, warming its climate by perhaps as much as 4.5 degrees Celsius (8 degrees Fahrenheit) over the next 50 to 100 years; shifting temperature zones and agriculture belts; altering rainfall patterns, storm frequencies and natural ecosystems; and possibly causing sea level to rise and inundate low lying coastal areas.

The increasing concentration of carbon dioxide, long predicted by some climate modelers to be the major cause of an adverse intensification of Earth's natural "greenhouse effect," is not the only variable in the atmospheric change equation. Although the possible climatic consequences of increasing carbon dioxide have been widely publicized and are the subject of an expanding international research effort, it is now thought possible that certain other infrared-absorbing trace gases could have a cumulative warming effect on climate comparable to that of carbon dioxide. Among the other greenhouse gases suspected of contributions to this possible global warming are: chlorofluorocarbons (CFCs), chlorocarbons, and Halons; methane; and nitrous oxide. Many of these gases have long residence times in the atmosphere, and their combined greenhouse warming effect may already be half as much as the cumulative warming from increasing carbon dioxide currently estimated by some models.

Three of the included papers in this section, one by H.F. Lins, E.T. Sundquist, and T.A. Ager, entitled "Information on Selected Climate and Climate-Change Issues" (*U.S. Geological Survey, Open-File Report 88-718,* 1988), one by G.J. MacDonald, entitled "Scientific Bases for the Greenhouse Effect" (*Journal of Policy Analysis* *and Management,* vol. 7, No. 3, 1988), and another by V. Ramanathan, entitled "The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment" (*Science,* vol. 240, Apr. 15, 1988) provide cogent summaries of the general scientific background on climate change issues. The U.S. Geological Survey paper includes a description of the Earth's atmosphere and its processes, an analysis of the 1988 drought, an explanation of the Earth's energy balance, trends in atmospheric composition of carbon dioxide and methane, an overview of "observed" global warming in the past and in the 1980s, and a discussion of the uncertainties in climate model predictions. The MacDonald paper also discusses most of these topics and includes, as well, a more complete explanation of the phenomenon called the "greenhouse effect" and a more detailed account of climate models and their capabilities and limitations. Likewise, Ramanathan elaborates on the greenhouse theory of climate change, its scope for verification, and the emerging complexities of feedback mechanisms in the climate system.

The problem of climate change is a complicated one because, while carbon dioxide and emissions of these other greenhouse gases may be warming the atmosphere, emissions of other compounds and gases, as well as a number of additional human activities and natural mechanisms now known to govern climatic change and variability, could mask, mimic, moderate, or even reverse a trace-gas-induced warming. The conclusion that a *drastically* reduced climate warming response will result from countervailing factors is, at least at the present time, not widely accepted, but the possibilities bear further consideration and study, as the article by V. Ramanathan, R.D. Cess, et al. on "Cloud-Radiative Forcing and Climate" (*Science,* vol. 243, Jan. 6, 1989) demonstrates.

The paper entitled "Unpleasant Surprises in the Greenhouse," by W.S. Broecker (*Nature,* vol. 328, July 9, 1987), discusses the uncertainties of our information about the responses of the atmosphere to forcing, such as the current increase of carbon dioxide concentration, and the possibility that global climate change could occur suddenly rather than gradually as numerical models predict. He points out that evidence of past climates from polar ice, bogs, and deep sea sediments seems to indicate that temperature changes in the past might have occurred in "leaps." He reviews pertinent ongoing and planned research and stresses the need for a long-term research strategy, identifying some specific areas of research needing greater attention.

In a broader sense, there is now a persuasive and widely held view in the scientific community and the Federal science agencies, as well as the international science community, that an improved, more fundamental understanding of the structure and functioning of Earth's natural systems and the forces that interconnect or change them is essential to protecting global habitability. The perceived need that has emerged over the last 15 years to study the climate system of the Earth, arising largely because of scientific findings that project possible warming of Earth's climate, has been foremost in contributing to this widely held view and to the rise of Earth system science—the notion that the Earth can best be understood as one interacting whole if the biosphere is studied together with the atmosphere, the world ocean, the land surface, the polar regions and the Sun. F.B. Wood in his article "The Need for Systems Research on Global Climate Change" (*Systems Research*, vol. 5, No. 3, 1988) emphasizes the complexities involved in studying global climate change and discusses this emerging consensus among natural scientists on the need for a broader earth systems perspective as a guide for research on global climate change and related areas.

The body of evidence adduced in favor of large-scale anthropogenic change poses important questions for all the nations of the world. Inadvertent alteration of the atmosphere, the ocean, or the land surface sets in motion forces that may profoundly affect conditions on the planet, both in the positive and negative senses. What are the implications of the changes in climate predicted by some models? For water supply? For food production? For human health and quality of life? For natural ecosystems and biological diversity? For coastal nations? To the extent certain changes can be identified as potentially detrimental, what can or should be done about them? How can we balance the risks and benefits of various courses of action? At what point does it become appropriate to take actions, perhaps global actions, to reduce those impacts that are potentially damaging? Global climatic change illustrates the complex mix of scientific, normative, and political questions inherent in such an issue as well as the importance of first developing a basis for sound scientific judgments through cooperative research efforts across disciplinary and national boundaries.

The paper by Sir Crispin Tickell, entitled *Implications of Global Climate Change*, was the keynote address at a Strategic Planning Seminar on the Long-Term Implications of Climatic Change, held January 5, 1988, in Washington, D.C. In this paper Sir Crispin raises many of these same questions, raising certain issues stemming from the state of our scientific knowledge on climate change, pointing out some of the implications of climate change, and stressing the international importance of climate change and relevant research efforts. In this same vein, the article by John C. Topping, Jr., "Where are We Heading in Responding to Climate Change?" (*International Environment Reporter*, October 1988), addresses the potential problems of climate change, identifies the host of international governmental, intergovernmental, and non-governmental interests and activities relevant to climate change research and implications, and suggests strategies which may be undertaken to reduce the sources and impacts of climate change.

27

INFORMATION ON SELECTED CLIMATE AND CLIMATE-CHANGE ISSUES

U.S. GEOLOGICAL SURVEY
Open-File Report 88-718

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

28

INFORMATION ON SELECTED CLIMATE AND CLIMATE-CHANGE ISSUES

By Harry F. Lins, Eric T. Sundquist, and Thomas A. Ager

U.S. GEOLOGICAL SURVEY

Open-File Report 88-718

U.S. DEPARTMENT OF THE INTERIOR

March 3 1849

Reston, Virginia

1988

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary
U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

For additional information
write to:

Office of the Director
U.S. Geological Survey
Reston, Virginia 22092

Copies of this report can be
purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Box 25425
Federal Center, Bldg. 810
Denver, Colorado 80225

PREFACE

During the spring and summer of 1988, large parts of the Nation were severely affected by intense heat and drought. In many areas agricultural productivity was significantly reduced. These events stimulated widespread concern not only for the immediate effects of severe drought, but also for the consequences of potential climatic change during the coming decades. Congress held hearings regarding these issues, and various agencies within the Executive Branch of government began preparing plans for dealing with the drought and potential climatic change. As part of the fact-finding process, the Assistant Secretary of the Interior for Water and Science asked the Geological Survey to prepare a briefing that would include basic information on climate, weather patterns, and drought; the greenhouse effect and global warming; and climatic change. The briefing was later updated and presented to the Secretary of the Interior. The Secretary then requested the Geological Survey to organize the briefing material in text form. The material contained in this report represents the Geological Survey response to the Secretary's request. The report is divided into three distinct sections, conforming to the three elements that composed the original briefings.

CONTENTS

Preface iii

The Weather and Climate System 1
by Harry F. Lins

- The General Circulation of the Atmosphere 1
- Zonal and Meridional Circulation 2
- Global Associations (Teleconnections) 3
- Precipitation Variability and Trends 4
- Drought 5
- The Drought of 1988 7
- The Drought in a Global Perspective 10

The Greenhouse Effect and Global Warming 11
by Eric T. Sundquist

- Critical Questions and Essential Facts 11
- Energy Balance of the Earth's Surface and Atmosphere 12
- Long-Term Changes in Atmospheric Carbon Dioxide 13
- Historical Changes in Atmospheric Carbon Dioxide 14
- Historical Changes in Atmospheric Methane 15
- Historical Global Warming 16
- Global Warming in the 1980's 17
- Predicting the Greenhouse Effect 18
- Major Uncertainties in Global Climate Model Projections 19
- Major Uncertainties in Regional Climate Predictions 20
- The Greenhouse Effect in a Geological Context 21

Climate Change in the Geologic Past 22
by Thomas A. Ager

- Perspectives on Long-Term Changes in Climate 22
- Climate Change During the Past 130 Million Years 23
- Milankovitch Forcing of Climate Change 24
- The Last 1,000 Years 25

References 26

THE WEATHER AND CLIMATE SYSTEM

by Harry F. Lins

The General Circulation of the Atmosphere

The global wind system, more specifically referred to as the general circulation of the atmosphere, functions to transport warm air from equatorial regions toward the poles, and to maintain a return flow of cold air from polar to tropical latitudes. It results from four primary conditions: solar radiation, the rotation of the Earth, the distribution of land masses and seas across the Earth's surface, and tidal forces. Solar radiation and the Earth's rotation combine to form the "brute force" driver of the system. They are, by far, the dominant factors. Topographic and thermodynamic differences arising from the spatial distribution of land and sea are major modulators of the brute force component. Tidal forces are minor modulators of brute force.

The general circulation has both vertical and horizontal structure (fig. 1). The vertical structure, composed of the tropical Hadley, mid-latitude Ferrel, and a very weak and intermittent polar cell, mixes heat and moisture through the depth of the atmosphere. The horizontal structure, manifest as the tropical trade winds, mid-latitude westerlies, and polar easterlies, performs the same function across the Earth's surface. These large-scale features primarily determine the broad pattern of global climate. Embedded within this large-scale system are smaller circulations which tend to perturb the global flow. These smaller-scale cyclonic (low pressure) and anticyclonic (high pressure) circulations are responsible for the transitory, short-term variations in atmospheric conditions, which we refer to as the weather.

Manuscript approved for publication
December 5, 1988

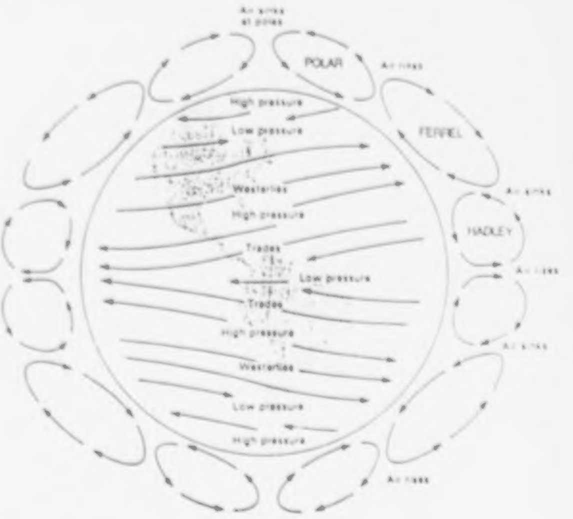

Air sinks at poles
POLAR
Air rises
High pressure
Low pressure
FERREL
Westerlies
Air sinks
High pressure
HADLEY
Trades
Low pressure
Air rises
Trades
Air sinks
High pressure
Westerlies
Low pressure
High pressure
Air rises

Figure 1. Schematic depiction of the general circulation of the Earth's atmosphere. (Source: Washington and Parkinson, 1986).

Zonal and Meridional Circulation

Large-scale movements of warm air poleward and cold air equatorward provide a balance between energy surpluses at low latitudes and energy deficits at high latitudes. When the temperature difference between high and low latitudes is relatively small, as is typical in summer, the circulation of the atmosphere is weaker and more zonal, or more nearly west to east (fig. 2). When the temperature contrast is high, as in winter, the circulation may become stronger and more meridional, or north-south. Thus, seasonal variations in weather patterns can typically be characterized by the persistence of one or the other of these two circulation regimes.

Changes in the amplitude of these planetary-scale circulation "waves" reflect the positions and intensities of high and low pressure systems around the globe. The region beneath a wave crest is characterized by high pressure. It is typically referred to as a high pressure "ridge." Such ridges serve to move relatively warm air poleward and are generally associated with fair weather conditions. The wave depressions are regions of low pressure, and are referred to as low pressure "troughs." Troughs of low pressure within the general circulation move relatively cold air equatorward and are generally associated with stormy conditions. Occasionally the amplitude of a low pressure trough becomes so great that the circulation folds back onto itself, thereby cutting the low pressure system off from the general circulation. Without the momentum provided by the general circulation such "cut-off" lows tend to persist over an area, sometimes bringing storminess for a week or more. In contrast, protracted periods of fair weather can accompany a high pressure ridge cut-off from the general circulation. Such ridges are frequently referred to as "blocking" highs, because they tend to block the movement of storm systems into an area.

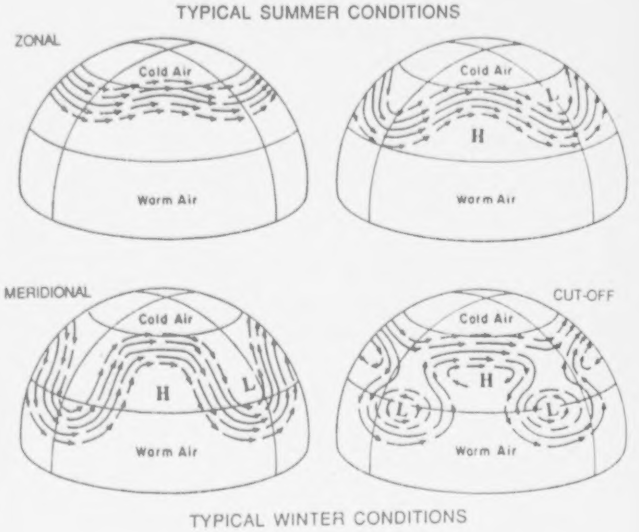
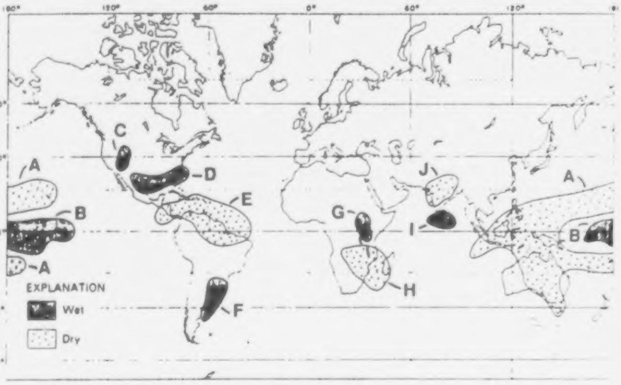


Figure 2. Zonal and meridional components of the horizontal circulation of the atmosphere. The letter L refers to low pressure and H to high pressure.

Global Associations (Teleconnections)

Recent research indicates that weather patterns in specific regions of the globe tend to exhibit consistent responses to certain large-scale atmospheric and oceanic circulations. These associations, frequently referred to as teleconnections, provide a basis for improving weekly weather prediction and seasonal climate forecasting. The concept of teleconnections actually refers to the statistical cross-correlation between atmospheric anomaly patterns (usually atmospheric pressure) separated by synoptic (1,000-2,500 km) to hemispheric distances.

The synoptic, or more proximal teleconnections are associated with variations in the location and intensity of the persistent subtropical high pressure regions (such as the Bermuda High) and subpolar low pressure regions (such as the Aleutian Low). The global, or more remote teleconnections stem from events such as El Nino-Southern Oscillation (ENSO). Research to date (1988) indicates that ENSO events generally coincide with distinct seasonal precipitation anomaly patterns, such as above normal precipitation along the Gulf and Southeast Atlantic coasts of the United States in winter and in the Great Basin in summer (fig. 3). High precipitation amounts also are found in southeastern South America in summer, the central Equatorial Pacific throughout the year, southern India in autumn, and east central Africa during the winter. Drought tends to accompany ENSO episodes in southeastern Africa in summer, most of India during the summer, northeastern South America and adjacent Caribbean basin in summer, and in a broad region of the western Pacific including Indonesia and Australia in various seasons.



LOCATION KEY

A - Indonesia, Australia, and western Pacific Ocean
B - Central Equatorial Pacific Ocean
C - Great Basin
D - Gulf and Southeast Atlantic Coasts of U.S.
E - Northeastern South America and Caribbean
F - Southeastern South America
G - East Central Africa
H - Southeastern Africa
I - Southern India
J - Northern and Central India

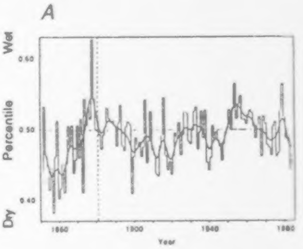
Figure 3. Regions exhibiting a consistent precipitation response signal to El Nino-Southern Oscillation episodes. (Source: Ropelewski and Halpert, 1987).

Precipitation Variability and Trends

Precipitation is a highly variable quantity both in space and time. Analysis of precipitation data for the Northern Hemisphere from the mid-19th century to the present (Bradley and others, 1987), and of much longer proxy series reconstructed from tree rings, indicate that significant regional variations have occurred over decadal and longer time scales. Hemispherically, decadal and longer fluctuations in precipitation are also evident, although there does not appear to be any systematic trend over the past century (fig. 4*A*).

Patterns in specific regions have been variable (fig. 4*B*). Europe, for example, has undergone a small but steady increase in precipitation since the 1860's. In the United States, precipitation declined between the 1880's and the 1930's. Since the 1930's, however, there has been a general increase with the most marked rise occurring since the mid-1950's. Precipitation over the Soviet Union has increased significantly since the 1880's, with most of the change occurring before 1900 and after 1940. In Northern Africa and the Middle East, precipitation exhibited little trend between 1900 and the late-1940's. Since then, however, precipitation has declined dramatically. In Southeastern Asia, a relatively wet period in the 1920's and early 1930's separated two protracted periods of relative dryness. The first was centered around 1900 and the second extended from the mid-1960's until the present.

During the past 30 to 40 years there have been some significant differences in the temporal distribution of precipitation on a latitudinal basis. In the middle latitudes (35° to 70° N), for example, a significant precipitation increase has occurred since 1940. In the subtropical latitudes (5° to 35° N), however, a significant decrease is evident since the mid-1950's. In the north equatorial region (0° to 5° N), little or no trend is evident in the record during the past century.



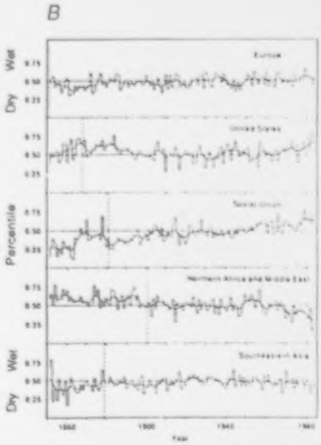


Figure 4. Annual precipitation index (mean of percentiles of the gamma distribution for Northern Hemisphere continental (*A*) and constituent regions (*B*). Vertical dashed line shows year in which 50 percent of the grid points became available for analysis. Curved line shows the smooth trend line fitted through individual values. (Source: Bradley and others, 1987)

Drought

In 1975 the World Meteorological Organization issued a Special Environmental Report on Drought. In that report, Helmut Landsberg, the father of American climatology, noted that after 50 years of climatological and statistical analyses it was clear that "drought is a recurrent phenomenon. There is no need to invoke climatic change as a cause each time drought occurs. Quite the contrary is evident: drought is an integral, if irregular, component of climate as it exists now" (Landsberg, 1975).

Part of the problem associated with understanding drought results from the fact that there are at least three different kinds of drought: meteorological, agricultural, and hydrological. Meteorological drought is generally defined in terms of lower than average precipitation for some time period. Agricultural drought refers to a shortage of water in the root zone of crops such that the yield of plants is reduced considerably (a lack of soil moisture). Hydrologic drought is defined in terms of low levels of streamflow, reservoir storage, ground water, or some combination of these. A drought episode may contain all three elements, two of them, or only one. Winter droughts, for example, are often only meteorological events since it is a time of little or no agricultural demand for water and generally lower water supply needs.

Drought is also highly variable both in space and time. In figure 5, standardized scores of the Palmer Drought Severity Index are plotted for nine regions around the United States. Several points are apparent from these plots. First, the occurrence of dry years varies considerably from region to region. Second, there is a relatively high year-to-year variability in nearly all regions. There does appear, however, to be some tendency for severe drought to persist over several years in the West North Central, Southwest, and South regions. Third, although some regions appear to exhibit decadal-scale trends toward both wetness and dryness, no region exhibits any systematic trend over secular time scales or over the 85-year period of record. In other words, the frequency of drought across the United States does not appear to have changed during the past century.

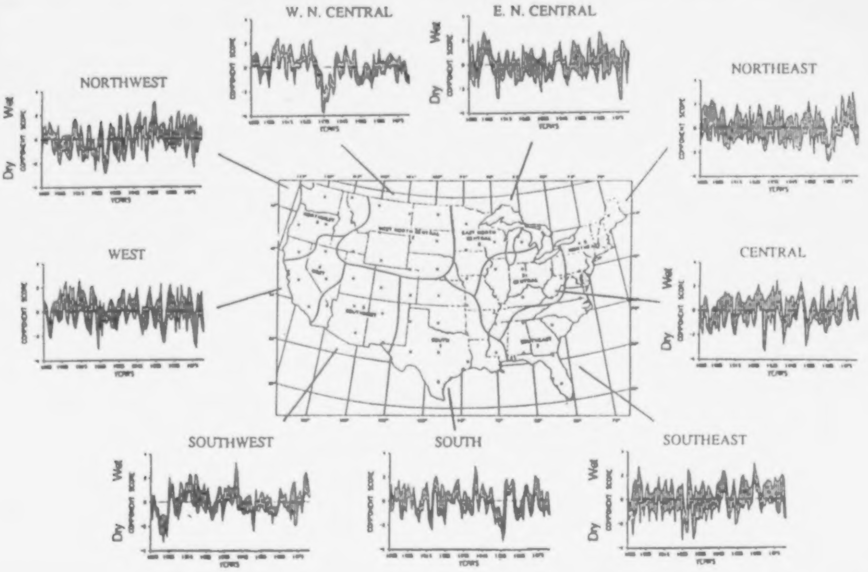


Figure 5. Annual maximum, minimum, and median principal component scores of the Palmer Drought Severity Index, 1895-1980. The plotted scores contrast years of relative wetness (above the zero line) with those of relative dryness (below the zero line). (Source: Karl and Koscielny, 1982).

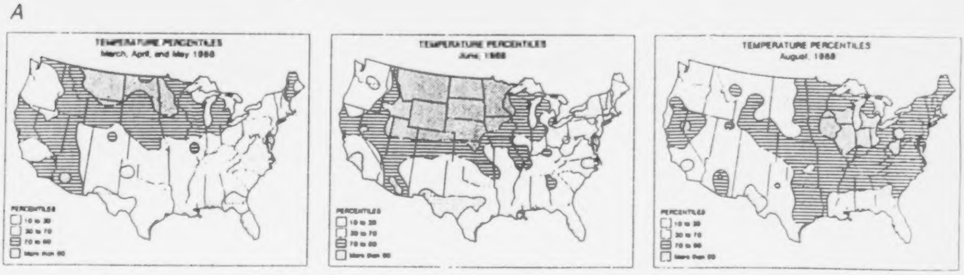
The Drought of 1988

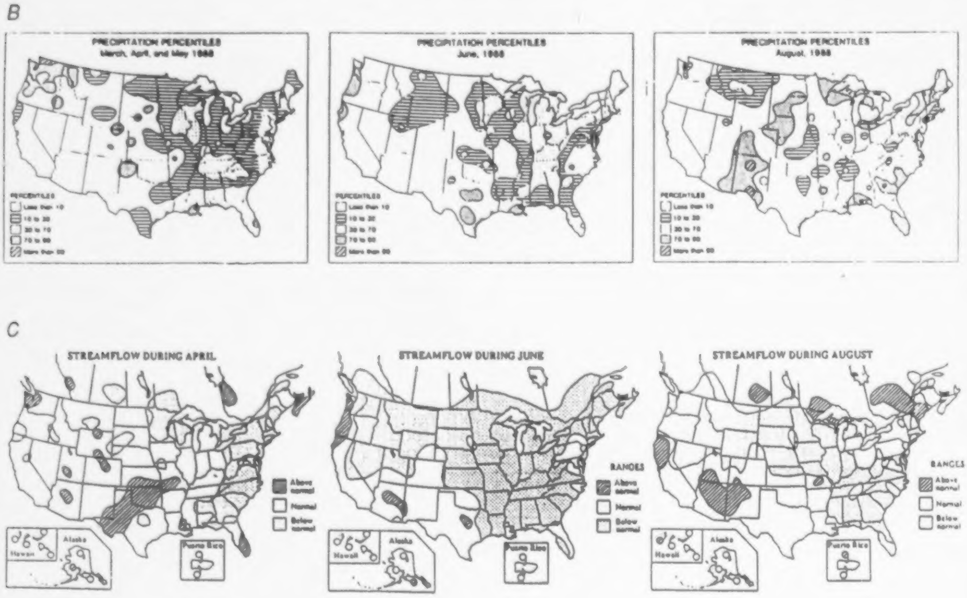
During the spring of 1988 a severe, though relatively short-term drought developed over the Northern Plains and Midwest regions of the United States. The conditions in these areas arose amidst longer-term drought that had been plaguing parts of the West since 1987 and parts of the Southeast since 1984. Although little was reported about these ongoing episodes, the event in the Nation's heartland quickly became a national news item.

The Northern Plains-Midwest drought had its beginnings in February when precipitation from the western Great Lakes to the Southern Plains was below to much-below normal. By March, the low precipitation coupled with above normal temperatures to begin widespread drying of soils in the northern half of the Great Plains. During April the situtation worsened as both below-normal precipitation and above-normal temperatures covered much of the Northern Plains and Midwest. Thus, at the critical time of plant germination, when soil moisture needs are relatively high, elevated temperatures and low precipitation severely depleted soil moisture reserves and reduced crop development (fig. 6*A* and *B*). Conditions continued deteriorating through June, with temperatures averaging 6 to 12 degrees F above normal over most of the Northern Plains and Midwest, with precipitation less than 40 percent of normal over much of the region (fig. 6 *A*, *B*, and *C*).

In July and August conditions began changing. Although temperatures remained above normal across much of the Nation throughout the summer, precipitation in the Northern Plains and Midwest returned to near normal conditions. Streamflow lagged behind precipitation in recovering as much of the rain went toward recharge and, because of the high temperatures, to increased evapotranspiration. Still, by summer's end the drought

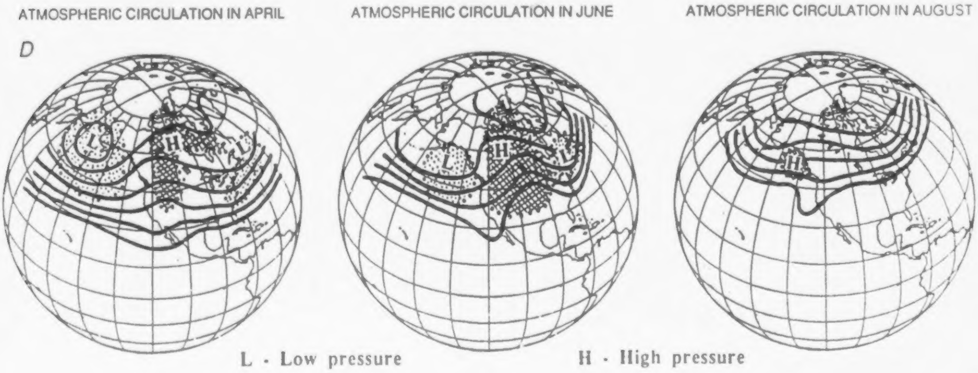
Figure 6. Sequences of meteorological and hydrological conditions across the United States during the spring season and the months of June and August. *A*, temperature. *B*, precipitation. *C*, streamflow. *D*, atmospheric circulation at the 10,000-foot level. (Sources: meteorological data - National Oceanic and Atmospheric Administration, National Weather Service and Climate Analysis Center; streamflow data - U.S. Geological Survey.)




B
PRECIPITATION PERCENTILES
March, April, and May 1988
PRECIPITATION PERCENTILES
June, 1988
PRECIPITATION PERCENTILES
August, 1988
PERCENTILES
Less than 10
10 to 30
30 to 70
70 to 90
More than 90
C
STREAMFLOW DURING APRIL
STREAMFLOW DURING JUNE
STREAMFLOW DURING AUGUST
RANGES
Above normal
Normal
Below normal
Hawaii
Alaska
Puerto Rico

of 1988 was essentially over in most parts of the Northern Plains and Midwest. Although this event was quite severe in a short-term sense, when considered in the context of drought over an entire year, 1988 may or may not be remembered as a great drought year. Conditions during October, November, and December will contribute significantly to how 1988 is recorded in the drought record books.

Perhaps of greater significance is the cause of this drought. Why did it occur? To answer this first question we need only look to the atmospheric circulation during the spring and summer months (fig. 6 *D*). During April, the circulation over the North American sector at 10,000 feet was characterized by abnormally deep troughs (stippled areas) of low pressure over the Aleutian Islands and Newfoundland with an abnormally strong ridge (cross-hatched area) of high pressure extending northward from the U.S. central Rockies to the Northwest Territories of Canada. This ridge was responsible for the warm, dry conditions that occurred at that time over the Northern Rockies and northern Great Plains. By June, the ridge of high pressure expanded drammatically to encompass more than half the U.S. and Canada. The abnormal intensity of this ridge lead to the unusally high temperatures and reduced precipitation across the central part of the country at that time. In July, however, and persisting in August, the circulation pattern changed as both the mid-continent high and the lows on both coasts broke down. In fact, the atmospheric circulation for both July and August was normal. This, in itself, didn't bring an end to the hot and dry condtions, since recovering from such conditions takes time. It did, however, signal an end to the abnormal circulation conditions which were directly responsible for the drought. Of course, the real question of what caused the drought is the question of what caused the circulation anomalies.


ATMOSPHERIC CIRCULATION IN APRIL

ATMOSPHERIC CIRCULATION IN JUNE

ATMOSPHERIC CIRCULATION IN AUGUST

The Drought in a Global Perspective

In recent years, a growing amount of evidence has been acquired indicating that atmospheric and oceanic conditions in one part of the globe affect the weather and climate in another part of the globe. The El Nino/Southern Oscillation is one of the most frequently cited examples. However, during the drought of 1988 there was no El Nino occurring in the tropical Pacific. So what can we say about the relation of this drought to regions of anomalous conditions elsewhere around the world? In short, nothing definitively at present. Although several scientists have hypothesized that the drought was linked to anomalously warm sea surface temperatures in the tropical Pacific (north of the El Nino region), this explanation has not yet gained general acceptance. In addition, despite the "teleconnections" or correlations between pressure patterns in one part of the world with those in another, most such correlations are weak to moderate and tend to be strongest during the winter season when pressure gradients are strongest. West central Canada, the area where the anomalous high pressure ridge was centered, is not a region where anomaly patterns correlate well with patterns elsewhere around the world in spring and summer (fig. 7). Moreover, the global meteorological anomalies during June, 1988 do not appear to reflect a global climate change. One can look at charts such as those in figure 7 for any month of the year, in any year, and see temperature and precipitation anomalies of similar or even greater spatial extent widely distributed around the world. There do not appear to be any trends evident in these anomalies that are in any way indicative of a condition differentiable from the natural variability of the climate system.

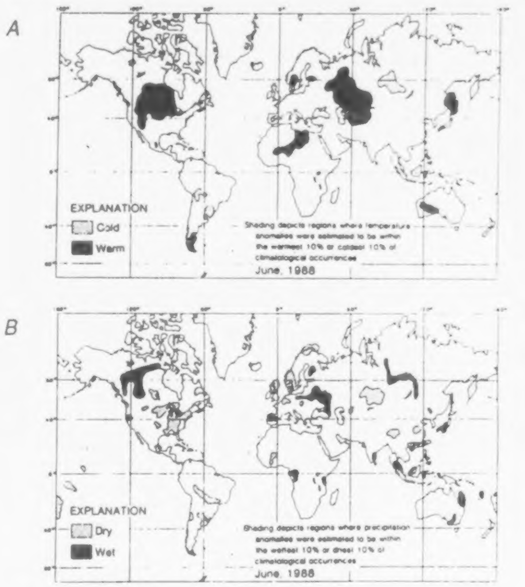

A
EXPLANATION
Cold
Warm
Shading depicts regions where temperature anomalies were estimated to be within the warmest 10% or coldest 10% of climatological occurrences
June, 1988
B
EXPLANATION
Dry
Wet
Shading depicts regions where precipitation anomalies were estimated to be within the wettest 10% or driest 10% of climatological occurrences
June, 1988

Figure 7. Global temperature (*A*) and precipitation (*B*) anomalies for June, 1988. (Source: National Oceanic and Atmospheric Administration, Climate Analysis Center).

THE GREENHOUSE EFFECT AND GLOBAL WARMING

by Eric T. Sundquist

Critical Questions and Essential Facts

Questions

Throughout the summer of 1988, the greenhouse effect received wide attention in the press and in a variety of public discussions throughout the world. This attention focused on several questions that are critical to our understanding of current climate and climate change, including:

- **What is the greenhouse effect?**
- **Does the current global warming confirm the greenhouse effect?**
- **Was the 1988 U.S. drought a result of the greenhouse effect?**
- **How well can the greenhouse effect be predicted?**

This section presents background information that is useful in the discussion of these questions.

Facts

The greenhouse effect is the absorption of long-wave radiation by certain gases in the Earth's atmosphere. This phenomenon has been documented and studied for more than a century. Although scientists continue to discover new and sometimes unexpected aspects of the greenhouse effect, the following points are now firmly established:

The greenhouse effect is a fact, not a theory. Its basic physical principles are well understood. The specific wavelengths of radiation absorbed by atmospheric trace gases are precisely known. The absorption of radiation by a gas causes its temperature to increase. The scientific challenge associated with the greenhouse effect is not to establish whether it exists, but rather to understand the manifestation of its basic physics throughout the Earth's immensely complex climate system.

The greenhouse effect is a natural phenomenon. The atmospheric gases which absorb the most long-wave radiation are water vapor and carbon dioxide, which have been present in the Earth's atmosphere for billions of years. Without the greenhouse effect of these two gases (and without the effect of clouds formed by the condensation of water vapor), the earth's average surface temperature would probably be near -18 degrees Celsius (0 degrees Fahrenheit).

The greenhouse effect was variable before human influence. There is good evidence for significant changes in the atmospheric concentrations of carbon dioxide and methane (another greenhouse gas) during the last 160,000 years.

The greenhouse effect is presently changing as a result of human activities. During the last 200 years, anthropogenic production of carbon dioxide has caused atmospheric concentrations to increase by 25 percent. Atmospheric methane concentrations have doubled. Other "greenhouse" gases -- nitrous oxide, halocarbons, and tropospheric ozone -- are also known to be increasing in the atmosphere at significant rates due to human activities. The combined influence of these changes in atmospheric composition is the principal reason for concern about present and future changes in the greenhouse effect.

Energy Balance of the Earth's Surface and Atmosphere

The complexity of the global climate system, of which the greenhouse effect is a part, is illustrated in figure 8. Pathways of incoming solar (short-wave) radiation appear in the dark-shaded areas on the left side of the illustration; pathways of long-wave radiation are depicted on the right. The units shown are relative to the total incoming solar radiation value of 100.

At the outer edge of the Earth's atmosphere, incoming solar short-wave radiation is balanced by predominantly long-wave outgoing radiation. The energy balance at the Earth's surface is dominated by long-wave radiation exchange with the atmosphere. The long-wave energy exchanged at the Earth's surface is much larger in magnitude than the amount of short-wave solar energy that reaches the Earth's surface. This amplication of the Earth-surface energy balance is caused by clouds and the greenhouse effect.

An idealized equilibrium energy balance is depicted in the figure. The units of incoming solar energy are exactly balanced by an equal number of units of outgoing radiation. In reality, the energy balance is currently shifting as a result of changing concentrations of greenhouse gases. The exact nature of this shift is very difficult to understand and predict because it involves all of the intricate feedbacks that comprise the Earth's climate system.

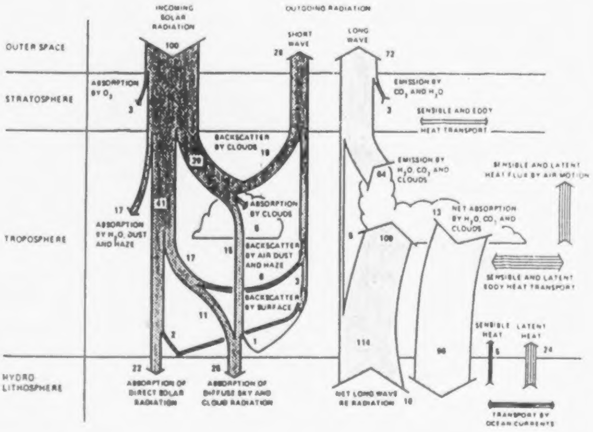

INCOMING SOLAR RADIATION
OUTGOING RADIATION
SHORT WAVE
LONG WAVE
OUTER SPACE
STRATOSPHERE
TROPOSPHERE
HYDRO LITHOSPHERE
100
28
72
ABSORPTION BY O$_3$
3
EMISSION BY CO$_2$ AND H$_2$O
3
SENSIBLE AND EDDY HEAT TRANSPORT
BACKSCATTER BY CLOUDS
19
39
EMISSION BY H$_2$O, CO$_2$ AND CLOUDS
64
SENSIBLE AND LATENT HEAT FLUX BY AIR MOTION
17
ABSORPTION BY H$_2$O, DUST AND HAZE
41
ABSORPTION BY CLOUDS
6
13
NET ABSORPTION BY H$_2$O, CO$_2$ AND CLOUDS
17
16
BACKSCATTER BY AIR DUST AND HAZE
6
5
109
SENSIBLE AND LATENT EDDY HEAT TRANSPORT
3
BACKSCATTER BY SURFACE
11
2
1
SENSIBLE HEAT
LATENT HEAT
114
96
5
24
22
26
ABSORPTION OF DIRECT SOLAR RADIATION
ABSORPTION OF DIFFUSE SKY AND CLOUD RADIATION
NET LONG WAVE RE RADIATION
18
TRANSPORT BY OCEAN CURRENTS

Figure 8. Energy balance of the earth's surface and atmosphere, in percent. (Source: Schneider and Mesirow, 1976).

Long-Term Changes in Atmospheric Carbon Dioxide

Evidence for changes in the greenhouse effect before human influence appears in figure 9. The plotted data are derived from analyses of a 2,000-meter ice core from Vostok, Antarctica, by a team of French and Soviet scientists (Barnola and others, 1987). The core contains ice deposited as snow over the last 160,000 years. Measurements of deuterium (an isotope of hydrogen) in the ice provide a record of the temperatures at which the ice was formed. Analyses of air bubbles trapped in the ice provide a corresponding record of past atmospheric compositions.

The lower curve in the graph shows deuterium values corresponding to the ages indicated on the lower axis. The record clearly shows relatively high deuterium values (corresponding to higher temperatures) during the last 10,000 years, lower values representing the last ice age, and high values for the preceding interglacial period from about 120,000 to 140,000 years ago. The upper curve shows carbon dioxide concentrations corresponding to the same time. The data show that atmospheric carbon dioxide and climate changes were closely related throughout the last 160,000 years. Ice core analyses for methane indicate a similar correlation with climate.

Unfortunately, it is not possible to separate past changes in climate and atmospheric composition into cause versus effect. Atmospheric carbon dioxide concentrations are very sensitive to changes in other components of the global carbon cycle, particularly the carbon contained in the oceans, plants, and soils. Although it is tempting to attribute past climate changes to the changing greenhouse effect, many hypothesized explanations for past carbon dioxide changes invoke climate change as a cause of carbon-cycle change. Like the climate system, the global carbon cycle contains many complex feedbacks which are all affected by a perturbation anywhere in the system.

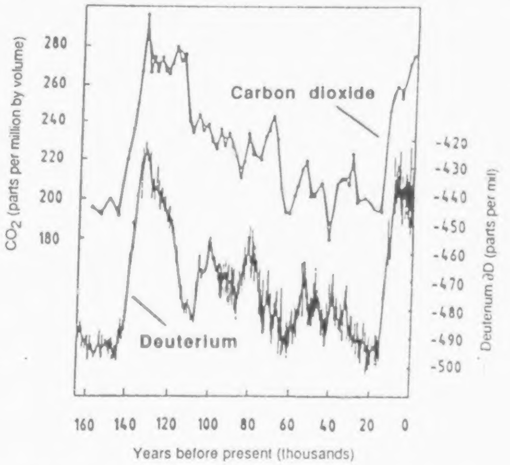


Figure 9. Long-term variations in carbon dioxide and deuterium as determined from the Vostok ice core (Source: Barnola and others, 1987).

Historical Changes in Atmospheric Carbon Dioxide

Analyses of ice cores from Greenland and Antarctica show that the atmospheric CO_2 concentration remained near 280 parts per million for nearly all of the 10,000 years since the end of the last ice age. Then, in the late eighteenth century, atmospheric CO_2 began to increase. The increase, determined by measuring ice core air bubbles and, beginning in the early 1950's, by continuous direct atmospheric measurements, appears in figure 10. The historic rate of increase has been exponential, rising to a present-day atmospheric CO_2 concentration of about 350 parts per million.

The source of this carbon dioxide increase is predominantly the burning of fossil fuels, with smaller contributions from changes in land use (for example, deforestation) and the production of cement from limestone. In fact, the total amount of CO_2 released by these activities during the last 200 years is about twice the amount of carbon dioxide that has remained as added atmospheric CO_2. The remainder of the anthropogenic carbon dioxide has been removed from the atmosphere by carbon-cycle exchange, primarily with the oceans. There is no doubt that the atmospheric CO_2 increase shown here is the result of human activities, but there is significant uncertainty about the response of the global carbon cycle to this perturbation in one of its key components.

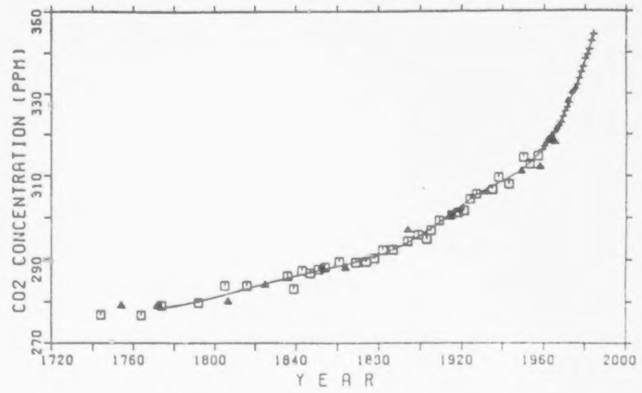


Figure 10. Variations in the concentration of atmospheric CO_2 as determined from ice cores in Greenland and Antarctica. (Source: Siegenthaler and Oeschger, 1987)

Historical Changes in Atmospheric Methane

The historical increase in atmospheric methane, derived from analyses of ice core air bubbles and, for the last decade, from direct atmospheric measurements, appears in figure 11. Although the relative increase in methane (from 800 to 1600 parts per billion) has been greater than that for CO_2, the sources of the methane increase are much less understood. The timing and magnitude of the change strongly indicate human influence. The most likely sources seem to be rice cultivation, enteric fermentation in animals, biomass burning, and fossil fuels. Unlike carbon dioxide, methane is actively consumed by chemical reactions in the atmosphere. However, because methane is not as readily absorbed by plants and the oceans, its average lifetime in the atmosphere may be greater than that of carbon dioxide. Predicting future concentrations of methane is very difficult because there are so many uncertainties about both its sources and sinks.

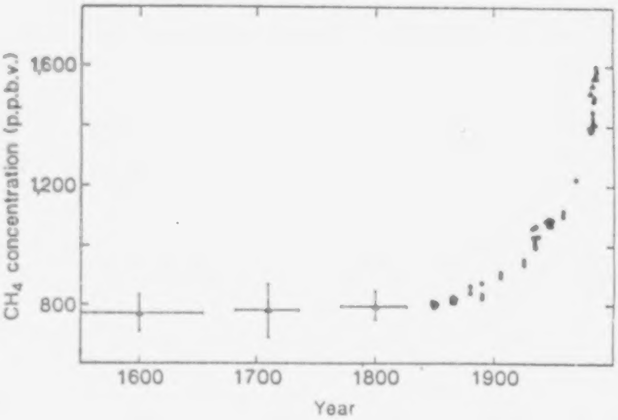


Figure 11. Atmospheric methane variations over the past few centuries. (Source: Pearman and Fraser, 1988).

Historical Global Warming

Historical mean global temperatures can be estimated using data from meteorological stations throughout the world. These stations are not uniformly distributed, however, and spatial averaging assumptions must, therefore, be applied to the stations that are available. Other corrections must be used for stations where measurement techniques or locations have changed during the period of record. Nevertheless, the data show a statistically significant global warming trend.

A graph of normalized mean global temperatures from 1880 through 1987, compiled by Hansen and Lebedeff (1988), appears as figure 12. The overall warming apparent in this record is close to 0.8 degrees Celsius (1.4 degrees Fahrenheit). Hansen and Lebedeff estimate that 0.1 to 0.2 degrees of this trend can be attributed to the heat released locally in urban areas, where many meteorological stations are located. Their estimate of the overall warming during the last century, including uncertainties, is 0.4 to 0.8 degrees Celsius (0.7 to 1.4 degrees Fahrenheit). This estimate is supported independently by other compilations (Jones and others, 1986), including analyses of sea surface temperature data. The average global warming over the last century is roughly consistent with the magnitude of warming expected from the increase in greenhouse gases during the same period.

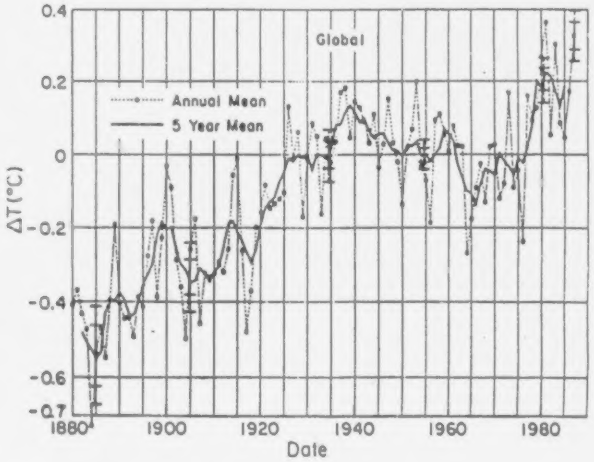


Figure 12. Normalized mean global temperatures, 1880-1987. (Source: Hansen and Lebedeff, 1988)

Global Warming in the 1980's

Global mean temperatures for the years 1980, 1981, 1983, and 1987 were the highest in the historical record. The high global mean temperatures in 1980, 1983, and 1987 were associated with pronounced warming at low latitudes. In particular, the temperature peaks of 1983 and 1987 were contemporaneous with "El Nino" conditions at low latitudes (figure 13). Historically, such events have often been followed within a few years by low latitude cooling ("La Nina" conditions) and a corresponding drop in mean global temperatures. In contrast to the observation that global warming in the 1980's has been associated primarily with low-latitude warming, climate model simulations of the effects of a greenhouse warming indicate that the warming should be most pronounced at high latitudes.

The global temperature data for early 1988 show continued warming. It is clear that the 1980's are the warmest period for which global mean temperatures can be reliably estimated from meteorological measurements (see figure 12). Does this confirm the presence of the anticipated CO_2-induced greenhouse warming? Although a few scientists have argued yes, most believe that it is too early to attribute the global warming to the greenhouse effect. Most scientists are reluctant to emphasize the warming of the 1980's more than the overall century-long warming trend. For example, the warming of the late 1930's was the warmest period in the record to that time, yet it was followed by three decades of cooler temperatures. Most scientists agree that, although the historical global warming is cause for serious concern, we cannot yet detect a climatic change caused by the greenhouse effect because it may be obscured by other causes of global temperature variation.

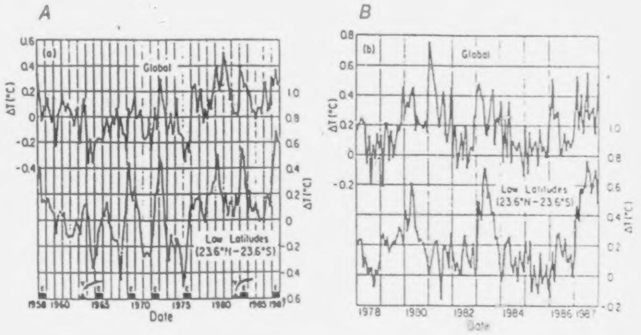


Figure 13. Global mean surface air temperature. *A*, Annual variations, 1958-1987. *B*, Monthly variations, 1978-1987. The letters **E** and **V** mark the years of major El Nino and volcanic eruptions, respectively. (Source: Hansen and Lebedeff, 1988)

Predicting the Greenhouse Effect

Predicting future climates is one of the most challenging and important scientific problems of our time. Predicting the climatic effects of trace gases requires the most sophisticated climate models and the most powerful supercomputers. Changes in mean global temperature and precipitation, as computed by five of the most widely cited atmospheric general circulation models (GCM's), are given in Table 1. These changes were computed for equilibrium climate conditions after a doubling of atmospheric CO_2, which is expected to occur sometime during the next century. Mean global temperatures are expected to increase by about 2 to 5 degrees Celsius, while mean global precipitation is predicted to rise by about 7 to 15 percent. The global precipitation increase is accompanied by a corresponding increase in the modeled global evaporation. The effects of increasing concentrations of trace gases other than CO_2 are expected to accelerate and add to the effects modeled here.

The significance of these predicted climate effects can be gaged by comparison to the estimated 5-degree Celsius mean global temperature change associated with the end of the last ice age. Unfortunately, there is no consistency among greenhouse predictions beyond the global equilibrium mean effects represented by the results shown in the table. There are still too many uncertainties in climate models to realistically predict regional effects, or to project changes that will occur during the time of transition to a new equilibrium climate.

Model/Study	Change in Temperature (°C)	Precipitation (Percent)
Geophysical Fluid Dynamics Laboratory / Wetherald and Manabe (1988)	4.0	8.7
Goddard Institute for Space Studies / Hansen and others (1984)	4.2	11.0
National Center for Atmospheric Research / Washington and Meehl (1984)	3.5	7.1
Oregon State University / Schlesinger and Zhao (1988)	2.8	7.8
United Kingdom Meteorological Office / Wilson and Mitchell (1987)	5.2	15.0

Table 1. Changes in the global mean surface air temperature (T_s) and precipitation rate (P) simulated by various atmospheric general circulation/mixed-layer ocean models for a CO_2 doubling. (Source: Schlesinger, 1988).

Major Uncertainties in Global Climate Model Projections

Many fundamental uncertainties are widely acknowledged throughout the climate and trace gas research communities. These include the following problems:

- Predicting **future greenhouse gas and aerosol emissions** requires a vast array of assumptions about future tech-nologies, economic and social developments, international relationships, and resource needs and availabilities.

- A thorough knowledge of the sources and sinks of atmospheric trace gases requires understanding the **global biogeochemical cycles** of carbon, nitrogen, sulfur, and related elements.

- Climate warming will be delayed by **ocean heat exchange**, which will absorb some of the heat retained in the atmosphere. Understanding this process will require coupling non-equilibrium models of atmospheric and oceanic circulation.

- Many climate model uncertainties are attributed to the **effects of clouds**, which can both enhance and attenuate warming at the earth surface, depending on their interactions with other feedbacks in the climate system.

- The **hydrologic cycle** is the most important and poorly understood component of energy and water exchange at the land surface.

- Climate modelers are increasingly emphatic that their work cannot yet be used to predict **anything on a regional scale.**

Major Uncertainties in Regional Climate Predictions

The following statement is representative of the consensus among climate modelers concerning predictions of regional effects such as droughts: "Although the results of the general circulation models often agree well with each other and with historical surface air temperature data over large scales (global/hemispheric/zonal), ... [they are] simply not yet ready to be used for quantitative prediction at anything approaching even a multi-state region, let alone a single surrogate gridpoint representing a particular state, county or city. Over such small scales, a wide range of responses is currently predicted" (Grotch, 1988).

The model results shown in figure 14 exemplify the differences among climate model simulations of regional effects. These plots show soil moisture simulated for three regions by two different general circulation models developed by the National Center for Atmospheric Research (NCAR) and the Geophysical Fluid Dynamics Laboratory (GFDL). Although these model simulations are not strictly comparable, they illustrate the inconsistencies among regional climate predictions. These differences in soil moisture projections reflect the models' disagreement on regional land surface water balances under greenhouse conditions. The solid curves approximate seasonal soil moisture trends for present atmospheric CO_2 levels, whereas the dashed curves represent equilibrium seasonal trends for increased CO_2 levels (doubled in the NCAR model; quadrupled in the GFDL model).

For the regions shown, there are obvious differences between the models in their simulations of both present-day and increased-CO_2 conditions. For the Great Plains, the GFDL model predicts decreased soil moisture with increasing CO_2. The NCAR model, however, predicts increased or nearly unchanged soil moisture for increased CO_2 in central North America. Clearly, it is premature to attempt to link regional drought to the greenhouse effect.

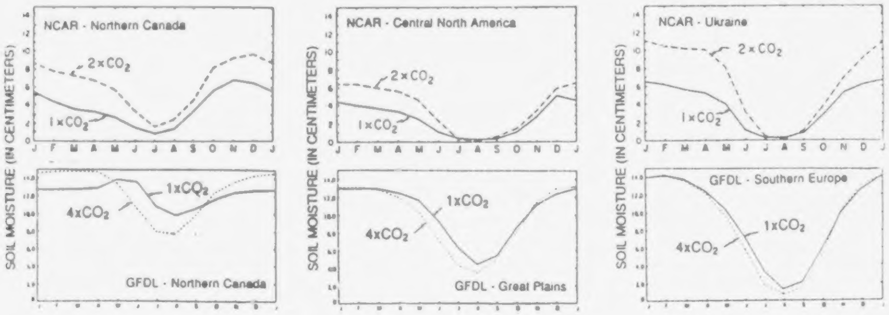


Figure 14. Annual cycle of soil moisture amounts (cm) averaged over several regions, as calculated by the National Center for Atmospheric Research (NCAR) and Geophysical Fluid Dynamics Laboratory (GFDL) general circulation models. (Source: Meehl and Washington, 1988).

The Greenhouse Effect in a Geological Context

Geologists have long hypothesized that changes in the greenhouse effect may have contributed to climate change in the geologic past. This possibility is strongly supported by the record of atmospheric climate and carbon dioxide and methane changes from ice cores. Thus, the geologic record offers the possibility of testing climate predictions using data from real past changes in the greenhouse effect and other climate parameters.

On the basis of the geological record of climate and atmospheric change, it appears that the present-day atmospheric CO_2 concentration is higher, as a result of human activities, than at any time during the last several hundred-thousand years. Hypothetical past and future atmospheric CO_2 levels are compared in figure 15. The diagram's time scale discontinuity (logarithmic for the left-hand section and linear for the right-hand side) emphasizes the extremely rapid rate at which future CO_2 concentrations may rise.

Most geologists believe that, to find geologic analogs of possible future atmospheric CO_2 levels, it is necessary to go back at least several million years in the geologic record. The evidence for higher atmospheric CO_2 concentrations in the distant geologic past is indirect, requiring inferences from sediment data and geochemical models. To relate this evidence to present and future changes in the greenhouse effect, we will need to acquire a much broader understanding of both the long-term processes that affected geologic carbon-cycle and climate change, and the short-term processes that will dominate trends during the coming decades and centuries.

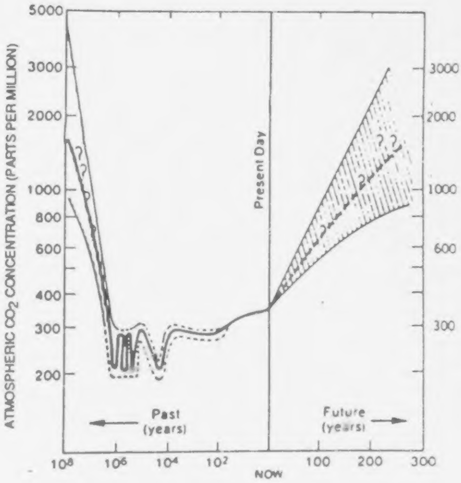


Figure 15. Overview of the history of atmospheric CO_2 from 10^8 years ago to the present day on a log-log scale. For comparison, the possible future CO_2 levels projected for the next few centuries are shown on a linear time scale. (Source: Gammon and others, 1985)

CLIMATE CHANGE IN THE GEOLOGIC PAST

by *Thomas A. Ager*

Perspectives on Long-Term Changes in Climate

Much of our understanding of the workings of the global climate system is based upon the instrumental meteorological observations that have been recorded systematically around the world during the past century. Our concept of what constitutes "normal" climate, therefore, is heavily influenced by average global climatic conditions covering only a short span of time. By examining the geologic record we can begin to see global climates from a much longer time perspective. We can look back far beyond the past century to see how variable climate has been during the past 1,000, 10,000, 100,000, or even millions of years.

Evidence of past climatic conditions is preserved in the geologic record in marine and lake sediments, in glacier ice, in peat and coal deposits, in cave deposits, coral reefs, and other stratified deposits. Innovative methods have been developed to extract information about past climates from geologic evidence and to date these past events by application of several isotopic techniques and other dating methods. It is, therefore, possible to reconstruct the broad outline of global climate history spanning many millions of years. More detailed climate reconstructions over time scales of centuries to tens of thousands of years are now available from many parts of the world. By examining changes in assemblages of climate-sensitive organisms represented by fossil remains over time, it is possible to reconstruct the consequences of past climate changes upon ecosystems in both marine and terrestrial environments. Studies of air bubbles and dust preserved in glacier ice provide insights into the changing composition of the atmosphere through time during the past 150,000 years. Ice core studies also allow us to document periods of time when volcanic eruptions were more frequent, when winds carried greater amounts of dust from the continents to distant ice sheets and ice caps.

The geologic record of past climate change provides insights into the causes and mechanisms of climate change, the rates at which some past climate changes occurred, and preserves important information about the effects of those changes on ecosystems, landscapes, and the oceans. The geologic record tells us that there is no single cause of climate change. Many factors influence global climate. The geologic record indicates that climate varies on all time scales due to natural causes. Those causes are not all well understood, or perhaps not all influences on climate are yet recognized. The causes and predictability of climate variation on time scales of greatest relevance to human populations (decades to centuries) are not well understood. To illustrate how much climate has varied in the past, global climate trends on several time scales will be briefly examined.

Climate Change During the Past 130 Million Years

A reconstructed temperature curve, spanning the past 130 million years, appears in figure 16. The curve reconstructs changes in the temperature of deep ocean waters at low latitudes over time. It is, therefore, colder than mean global air temperatures. Nevertheless, it is useful for illustrating the probable global temperature trends over that very long time interval. The curve shows that the dominant trend over the past 130 million years has been toward cooler climatic conditions. Superimposed upon this long-term trend are significant temperature oscillations that lasted up to several million years. These periodic warming and cooling events had significant impacts upon global ecosystems both in the marine and terrestrial realms. Causes of these long-term and intermediate-term climate trends are not well understood. On time scales of tens of millions of years, however, plate tectonics influenced global climate by shifting the positions of continents, causing intervals of mountain building and volcanic activity, and influencing the distribution and depths of oceans and seas. All of these factors influence global climate. The gradual shift of continental land masses into polar latitudes, and the opening of the Atlantic Ocean were important factors contributing to long-term cooling trends during the past 100 million years. Intense volcanism can cause short-term cooling of climate by injecting ash particles into the stratosphere, where the ash reflects incoming radiation into space. Prolonged volcanism may cause longer-term climate change by altering the atmosphere's carbon dioxide content. High mountain ranges influence atmospheric circulation patterns and serve as accumulation centers for ice and snow.

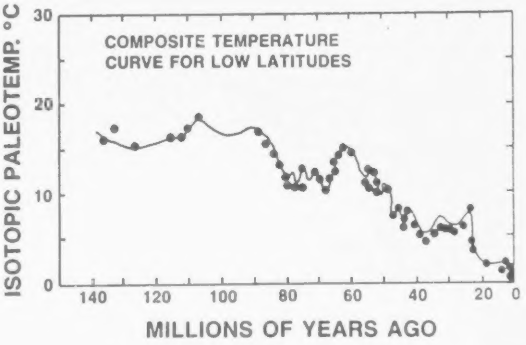


Figure 16. Deep sea water temperature history for the past 130 million years. (Source: Douglas and Woodruff, 1981).

About 2.5 million years ago the climate regime of the Earth changed into an unusual mode of high amplitude oscillations between long intervals of cool or cold climate interrupted by generally shorter intervals of warmer climate. The reasons for this shift are not completely clear. The emergence of the Isthmus of Panama and the opening of the Bering Strait about 3 million years ago altered oceanic circulation patterns, and these events may have contributed to the change in global climate pattens.

One of the causes of the major climatic oscillations during the past million years, however, has been identified. During the 1920's and 1930's a theory was developed by a Yugoslavian engineer and mathematician, Milutin Milankovitch. According to his theory, the sequence of ice ages periodically interrupted by warmer interglacials and interstadials of the past million years could be largely explained by celestial mechanics. By calculating the changes in the Earth's orbital parameters through time -- axial precession, axial tilt, and orbital eccentricity -- Milankovitch showed that different latitudes would receive differing amounts of solar energy over time scales of tens of thousands to hundreds of thousands of years. The theory could not be tested adequately until the past two decades or so, when detailed studies of marine sediment cores from all around the world showed strong agreement between the frequencies of past environmental changes and Milankovitch's calculated sequence of solar insolation changes. The chronology of past ice ages and warm interglacials fit the predictions of the theory quite well. The Milankovitch theory does not explain all the observed variation in global climates of the past million years, but it does show that orbital geometry has been the dominant influence on time scales of tens of thousands of years or more. Projecting the orbital parameters into the future indicates that if human influence on the greenhouse effect were not of immediate concern, we might instead be concerned about the gradual onset of a new glacial interval. It would probably require 10,000 years to attain full-glacial conditions, however. Even the early stages of a global cooling could have serious consequences for human populations.

Oxygen isotope variations measured from fossil foraminifera preserved in low latitude marine sediment cores during the past 750,000 years are plotted in figure 17. The isotopic variations were initially believed to reflect sea surface temperature changes through time. Later work indicated that changes in global ice volume also contribute to variations in isotopic composition of foraminifera. A temperature scale added to the curve (figure 17) shows that the global mean annual temperature (MAT) has varied about 1°C (1.8 degrees F) above current MAT and as much as 5°C (9 degrees F) below current MAT during the past 750,000 years. The peaks in the curve that intersect the dashed line indicate past intervals of warm interglacial climates. The current interglacial has lasted for about 10,000 years, and the record indicates that past interglacials lasted about 8,000 to 12,000 years. Such warm intervals have been relatively rare during the past 2.5 million years and intervals warmer than today are even rarer over that time. Only a few percent of that time has been characterized by global temperatures comparable to that of the present time. Some climate models predict that global mean annual temperatures may rise 2 to 5 degrees Celsius (3.6 to 9.0 degrees F) above the present mean temperature as a result of human influence on the greenhouse effect. If that prediction proves to be correct, such a global warming would have no precedent in the Earth's climatic history during the past 2.5 million years or more. Many of the organisms now living on earth evolved during the past several million years of generally cooler climates. It may be difficult, therefore, to predict how these species, and the ecosystems that they are a part of, would react to a rapid global warming of such magnitude.

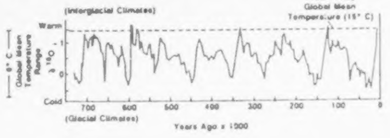
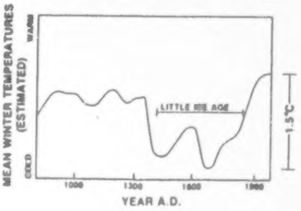


Figure 17. Composite oxygen isotope curve for the past 750,000 years of Earth history. (Source: Emiliani, 1978).

The Last 1,000 Years

Even during the past 10,000 years of a warm interglacial climate (the Holocene), the time span during which human civilization developed, there have been oscillations of global climate of sufficient magnitude to significantly influence human history. Global mean temperatures oscillated about 1.0 degree Celsius or more above and below the present mean value during the Holocene. Climate change of that magnitude is sufficient to cause glacier advances and retreats in alpine and polar regions, and to significantly impact human populations in many parts of the world. Changes in crop yields, the types of crops that could be raised, and the frequency of crop failures were some of the manifestations of Holocene climate fluctuations. The Norse colonization of Greenland occurred during a warm interval that permitted settlers to grow oats, rye, and barley. Declining temperatures between about 1250 A.D. and 1450 A.D. led to the disappearance of the Greenland colonies as agriculture became precarious and sea ice drifted farther and farther south., inhibiting contact with Europe. Cold temperatures persisted in Europe between about 1430 A.D. and 1850 A.D. This cold interval is called the "Little Ice Age." The hardships caused by this long interval of severe winters and more frequent crop failures is preserved in the art, literature, and commercial records of the time. Glaciers advanced in the mountains of Europe and Alaska during the Little Ice Age. Yet the magnitude of the global temperature change (about 1 degree C) was small in comparison with the temperature decline during the coldest pan of the major glacial intervals during the past 1 million years (about 5 degrees C colder than the present global mean).

There is currently a controversy about the significance of an apparent increase of about 0.6 degree C in the global mean annual temperature during the past century. One part of the controversy relates to whether the meteorological data are sufficiently reliable to detect a change of that magnitude averaged globally. The other part of the controversy is whether or not the temperature increase, if it is real, represents natural variation in climate or whether it is an early manifestation of the changing greenhouse effect from increases in carbon dioxide and other trace gases in the atmosphere during the past century of intense industrial development and population growth. From the geologic perspective, the apparent temperature rise of the past century may simply represent a natural warming trend that is part of the oscillation toward warmer conditions following the end of the Little Ice Age (figure 18).



The potential for human influence on climate appears to be a valid concern for the world's human populations. The global climate system is complex and poorly understood and, therefore, it is very difficult to predict its future response to human influences such as changes in the composition of the atmosphere. It is important to keep in mind, however, that there is a large amount of natural variability in the climate system. It is, therefore, premature to attribute individual "unusual" climate events such as the drought of 1988 in the United States or the succession of "warmer-than-normal" years during the 1980's to the anthropogenic enhancement of the greenhouse effect at this time. Historical data provide a brief glimpse of this natural variability, and the geologic record documents significant natural variability over a broad spectrum of time scales. Anticipating future climate change will require understanding not only the future greenhouse effect, but also the naturally variable climate system.

Figure 18. Winter temperature estimates for Eastern Europe during the past 1,000 years, based largely on historic non-instrumental records. (Source: Lamb, 1977).

REFERENCES

Barnola, J.M., Raynaud, D., Korotkevich, Y.S., and Lorius, C., 1987, Vostok ice core provides 160,000-year record of atmospheric CO2: Nature, v. 329, p. 408-414.

Bradley, R.S., Diaz, H.F., Eischeid, J.K., Jones, P.D., Kelly, P.M., and Goodess, C.M., 1987, Precipitation fluctuations over Northern Hemisphere land areas since the mid-19th century: Science, v. 237, p. 171-175.

Douglas, R.G., and Woodruff, F., 1981, Deep sea benthic foraminifer, *in* Emiliani, C., ed., The Sea: v. 7, New York, Wiley, p. 1233-1327.

Emiliani, C., 1978, The cause of the ice ages: Earth and Planetary Science Letters, v. 37, p. 349-354.

Gammon, R.H., Sundquist, E.T., and Fraser, P.J., 1985, History of carbon dioxide in the atmosphere: United States Department of Energy, Atmospheric Carbon Dioxide and the Global Carbon Cycle, Chp. 3, p. 25-62.

Grotch, S.L., 1988, Regional intercomparisons of general circulation model predictions and historical climate data: United States Department of Energy TR041, 291 p.

Hansen, J., and Lebedeff, S., 1988, Global surface air temperatures: Update through 1987: Geophysical Research Letters, v. 15, p. 323-326.

Hansen, J., Lacis, A., Rind, D., Russell, G., Stone, P., Fung, I., Ruedy, R., and Lerner, J., 1984, Climate sensitivity: analysis of feedback mechanisms, *in* Hansen, J., and Takahasi, T., eds., Climate processes and climate sensitivity: Washington, D.C., American Geophysical Union, p. 130-163.

Jones, P.D., Wigley, T.M.L., and Wright, P.B., 1986, Global temperature variations between 1861 and 1984: Nature, v. 322, p. 430-434.

Karl, T.R., and Koscielny, A.J., 1982, Drought in the United States: 1895-1981: Journal of Climatology, v. 2, p. 313-329.

Lamb, H.H., 1977, Climate: present, past and future, v. 2 Climatic history and the future: London, Methuen and Co. Ltd., 835 p.

Landsberg, H.E., 1975, Drought, a recurrent element of climate: *in*, Drought, Special Environmental Report No. 5, Geneva, World Meteorological Organization, p. 41-90.

Meehl, G.A., and Washington, W.M., 1988, A comparison of soil-moisture sensitivity in two global climate models: Journal of Atmospheric Sciences, v. 45, p. 1476-1492.

Pearman, G.I., and Fraser, P.J., 1988, Sources of increased methane: Nature, v. 332, p. 489-490.

Ropelewski, C.F., and Halpert, M.S., 1987, Global and regional scale precipitation patterns associated with the El Nino/Southern Oscillation: Monthly Weather Review, v. 115, p. 1606-1626.

Schlesinger, M.E., 1988, Model projections of the climatic changes induced by increased atmospheric CO_2: Proceedings volume, Symposium on Climate and Geo-Sciences, Louvain-la-Neuve, Belgium.

Schlesinger, M.E., and Zhao, A.-C., 1988, Seasonal climatic changes induced by doubled CO_2 as simulated by the OSU atmospheric GCM/mixed-layer ocean model: Report No. 70, Climatic Research Institute, Corvallis, Oregon State University, 73 p. (in press).

Schneider, S.H., and Mesirow, L.E., 1976, The genesis strategy: climate and global survival: New York, Plenum.

Siegenthaler, U., and Oeschger, H., 1987, Biospheric CO_2 emissions during the past 200 years reconstructed by deconvolution of ice core data: Tellus, v. 39B(1-2), p. 140-154.

Washington, W.M., and Meehl, G.A., 1984, Seasonal cycle experiment on the climate sensitivity due to a doubling of CO_2 with an atmospheric general circulation model coupled to a simple mixed-layer ocean model: Journal of Geophysical Research, v. 89, p. 9475-9503.

Washington, W.M., and Parkinson, C.L., 1986, An introduction to three-dimensional climate modeling: Mill Valley, CA, University Science Books, 422 p.

Wetherald, R., and Manabe, S., 1988, Cloud feedback processes in a general circulation model: Journal of Atmospheric Sciences (in press).

Wilson, C.A., and Mitchell, J.F., 1987, A doubled CO_2 climate sensitivity experiment with a global model including a simple ocean: Journal of Geophysical Research, v. 92, p. 13,315-13,343.

Scientific Basis for the Greenhouse Effect

Gordon J. MacDonald

Abstract

Carbon dioxide and a wide variety of other industrial gases, including methane, ozone, and freon, trap a portion of the earth's thermal radiation that would otherwise escape into space. This radiative trapping of energy produces the heating of the atmosphere popularly labeled the greenhouse effect. Detailed observations from remote stations show that the carbon dioxide concentration of the atmosphere has increased from 316 parts per million by volume (ppmv) in 1958 to 350 ppmv in 1986. The exponential growth in carbon dioxide levels parallels the increased worldwide use of carbon-based fuels. Methane concentrations are increasing at a rate of one to two percent per year, lower atmosphere ozone at a somewhat smaller rate, and freons at a current rate of five percent per year. Calculations of the expected increase in the average temperature of the earth's surface since 1900 lead to a value of about 0.5 °C if the moderating effect of the earth's oceans is taken into account. Calculations are based on models that range in complexity from simple energy balance considerations to detailed three-dimensional calculations that strain the capacity of current digital computers. Detailed analysis of tens of millions of surface-temperature observations indicate an average warming of about 0.5°C since the turn of the century and a greater warming of 2°C in high latitudes. Major climatic shifts can be expected as the warming proceeds at an increasing pace. The rate of anticipated warming is historically unprecedented.

INTRODUCTION

Compared with the intense heat of Venus, or the stark day-night contrast of Mars and the moon, the earth possesses a relatively equable climate that makes possible the existence of man. The favorable nature of the earth's climate is made possible by the beneficial interactions of the oceans, atmosphere, and biosphere. A primary descriptor of climate, though by no means the only one, is temperature, which depends on the delicate balance between

Journal of Policy Analysis and Management, Vol. 7, No. 3, 425–444 (1988)
© 1988 by the Association for Public Policy Analysis and Management
Published by John Wiley & Sons, Inc. CCC 0276-8139/88/020425-20$04.00

the incoming, short-wavelength radiation of the hot sun and the outgoing radiation of the much cooler earth.

If the atmosphere were stripped away, the average temperature of earth's surface would be an inhospitable 35 °C colder than it is today. The atmosphere provides a warming blanket for the surface through the action of certain constituents whose concentrations are much smaller than that of the dominant nitrogen and oxygen. Water vapor, carbon dioxide (CO_2), and ozone (O_3) are the most important of these species, though a myriad of other constituents contribute to the warming.

The oceans play an important role in determining climate by providing a gigantic reservoir for water (and carbon dioxide) and also through their large thermal inertia. Without the stabilizing oceans, our climate would be much more variable. The biosphere also serves as a source and sink for climate-controlling constituents of the atmosphere. By determining, in part, the reflective nature of the earth's surface, the biosphere also partly controls the fraction of the sun's radiation that is reflected back into space without interacting thermally with the surface and atmosphere.

Weather and climate are important determinants of regional character. The day-to-day fluctuations of the atmosphere make up weather. By convention, normal climate is taken as a moving 30-year average of weather. The 30-year standard is an attempt to balance the practical limitation of data accumulation with statistical requirements for stable measures. Despite the artificiality of such definitions, it is clear that weather and climate influence a region's energy use, growth of plants and animals, means of transportation, water supplies, natural areas, pattern of habitation—in brief, its infrastructure. A combination of temperature and availability of moisture determines whether vegetation is forest, prairie, tundra, or desert, and also the ease with which society can adapt to natural stresses. The frequency of such extreme events as tornadoes, hurricanes, floods, and droughts affects the habitability of a region and the investments required to moderate economic, physical, and social stresses created by weather and climate. The entire physical and economic infrastructure of a region is an adaptation to the prevailing climate, an adaptation developed over centuries.

Climate change refers to shifts in normal climate lasting over decades. Year-to-year events, such as several years of extremely dry or wet conditions, are variations in climate—not climate change—if they are within the expected statistical deviations for normal climate. Decades-long trends in regional climate, such as the gradual change of a tropical savanna to a desert, constitute climate change. Global climate change refers to shifts, generally in the same direction, over all parts of the planet. For example, the Little Ice Age, dating from about 1500 to 1850 A.D., involved a global cooling with an extension of sea ice in both the northern and southern hemispheres. The Little Ice Age thus qualifies as climate change.

Global climate changes have had a profound effect on human history.[1] Only 18,000 years ago, a several-kilometers-thick ice sheet covered much of Canada, northern United States, and northern Europe. During the period 8000 to 4000 years before the present (B.P.), conditions were warmer than today by perhaps as much as 1 °C to 2 °C, with precipitation zones shifted northward. About 1000 years B.P., relatively warm temperatures allowed the Norse to cross the North Atlantic. With the Little Ice Age came temperatures a few tenths of a degree Celsius colder than today. Not only were temperathe incoming, short-wavelength radiation of the hot sun and the outgoing radiation of the much cooler earth.

If the atmosphere were stripped away, the average temperature of earth's surface would be an inhospitable 35 °C colder than it is today. The atmosphere provides a warming blanket for the surface through the action of certain constituents whose concentrations are much smaller than that of the dominant nitrogen and oxygen. Water vapor, carbon dioxide (CO_2), and ozone (O_3) are the most important of these species, though a myriad of other constituents contribute to the warming.

The oceans play an important role in determining climate by providing a gigantic reservoir for water (and carbon dioxide) and also through their large thermal inertia. Without the stabilizing oceans, our climate would be much more variable. The biosphere also serves as a source and sink for climate-controlling constituents of the atmosphere. By determining, in part, the reflective nature of the earth's surface, the biosphere also partly controls the fraction of the sun's radiation that is reflected back into space without interacting thermally with the surface and atmosphere.

Weather and climate are important determinants of regional character. The day-to-day fluctuations of the atmosphere make up weather. By convention, normal climate is taken as a moving 30-year average of weather. The 30-year standard is an attempt to balance the practical limitation of data accumulation with statistical requirements for stable measures. Despite the artificiality of such definitions, it is clear that weather and climate influence a region's energy use, growth of plants and animals, means of transportation, water supplies, natural areas, pattern of habitation—in brief, its infrastructure. A combination of temperature and availability of moisture determines whether vegetation is forest, prairie, tundra, or desert, and also the ease with which society can adapt to natural stresses. The frequency of such extreme events as tornadoes, hurricanes, floods, and droughts affects the habitability of a region and the investments required to moderate economic, physical, and social stresses created by weather and climate. The entire physical and economic infrastructure of a region is an adaptation to the prevailing climate, an adaptation developed over centuries.

Climate change refers to shifts in normal climate lasting over decades. Year-to-year events, such as several years of extremely dry or wet conditions, are variations in climate—not climate change—if they are within the expected statistical deviations for normal climate. Decades-long trends in regional climate, such as the gradual change of a tropical savanna to a desert, constitute climate change. Global climate change refers to shifts, generally in the same direction, over all parts of the planet. For example, the Little Ice Age, dating from about 1500 to 1850 A.D., involved a global cooling with an extension of sea ice in both the northern and southern hemispheres. The Little Ice Age thus qualifies as climate change.

Global climate changes have had a profound effect on human history.[1] Only 18,000 years ago, a several-kilometers-thick ice sheet covered much of Canada, northern United States, and northern Europe. During the period 8000 to 4000 years before the present (B.P.), conditions were warmer than today by perhaps as much as 1 °C to 2 °C, with precipitation zones shifted northward. About 1000 years B.P., relatively warm temperatures allowed the Norse to cross the North Atlantic. With the Little Ice Age came temperatures a few tenths of a degree Celsius colder than today. Not only were temperatures lower, but there was an increased variability in climate with numerous years of famine and plague well documented in Europe.

We now recognize that man's activities can bring about changes in climate in addition to those due to the natural fluctuations and long-term evolution of the atmosphere. Before 19th-century industrialization, man's activities were of too small a scale and too low an intensity to alter global climate. With the mechanization of agriculture and the greatly enhanced use of carbon-based fuels, particularly coal, the situation changed. Both the burning of coal and the greater development of agriculture released carbon that had been stored in the soil and rocks for thousands or millions of years. Once released, carbon forms atmospheric carbon dioxide and the composition of the atmosphere is changed, perhaps irreversibly. Of all of man's myriad activities, none has brought about as pervasive and large-scale an alteration as that of the composition of the atmosphere resulting from agriculture and energy use.

Though J. Tyndale[2] recognized that slight changes in atmospheric composition could bring about climate variation as early as 1861, it was not until 1938 that G. Callendar[3] showed how man, by burning carbon-based fuels, was capable of changing the climate of the planet. The subject of anthropogenic climate change is thus only 50 years old. Intensive study began with the heightened interest in the environment during the late 1960s. The last decade has seen two major advances in understanding climate change. Carbon dioxide, once thought to be the sole culprit, is not alone in changing atmospheric thermal balance; other gases, taken together, are of comparable importance. Stated in another way, when looking toward the future the problem is twice as severe. The second discovery is that the earth's surface in the 1980s is 0.5 °C warmer than it was during the 1880s. The change has not gone smoothly over the years; but despite the erratic course of earth's temperature, it is clearly moving in the direction of global warming in accord with theoretical expectations.

THE ATMOSPHERE AS A GREENHOUSE

The hot surface of the sun radiates as a body having the equivalent temperature of 5800 °K. The bulk of the radiation is in the visible-wavelength region, 0.4 to 1.0 μm, where earth's atmospheric gases absorb only weakly. In contrast, the low temperature earth emits radiation at infrared wavelengths, which the atmosphere highly absorbs, as is illustrated in Figure 1. In an oversimplified description, the atmosphere lets shorter-wavelength radiation in, but does not let the longer-wavelength radiation out. By supposed analogy with the behavior of panes of glass, the result is called the *greenhouse effect*. In reality, greenhouses do not depend on trapping radiation for their warmth, but rather inhibit cooling of the plants due to moving air; thus, thin plastic works just about as well as glass.

The earth's thermal radiation is mainly confined to the 5–30-μm region (see Figure 1). Between 0.54 and 8 μm and longward of 18 μm, water vapor has strong absorption bands. For typical values of humidity, the atmosphere is opaque to the earth's thermal radiation in the indicated regions. Thermal radiation peaks in the critical 8–18-μm region, where water is a weak absorber. The 12.5–18-μm region is largely blocked by carbon dioxide absorp-

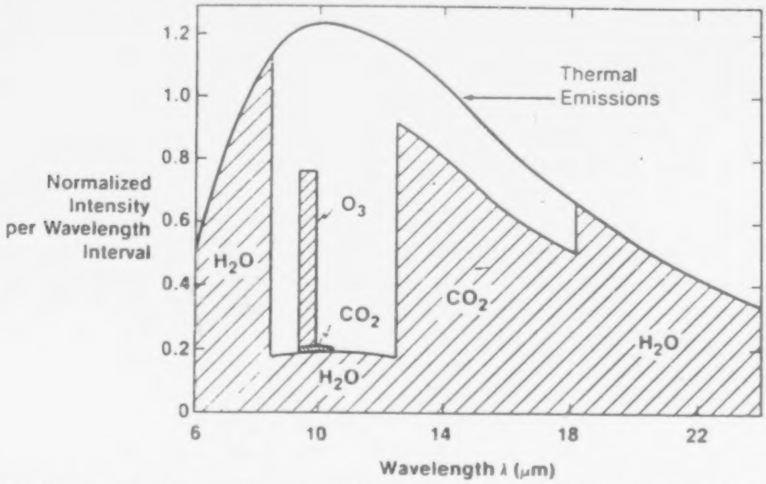


Figure 1. Relative values of atmospheric absorption of earth's thermal emissions. Thermal emissions of the earth's surface at a temperature of 290°K indicated by heavy curve. The shaded area represents that portion of the thermal emission that is absorbed by the indicated constituents. The figure illustrates why trace amounts of absorbers in the 8.5–12.5-μm (micron) region can be critically important in determining the thermal balance of the atmosphere.

tion. This leaves a window of relative transparency between 8.5 and 12.5 μm so that energy radiated from the earth's surface at these wavelengths flows relatively freely into space. A portion of the window is blocked by the 9.6-μm absorption band of ozone. The fraction of the earth's radiation that is absorbed by the atmosphere, indicated by the shaded region in Figure 1, is available to heat the atmosphere. In turn, the atmosphere radiates heat away at an equilibrium temperature determined by the intensity of the earth's thermal emission and the amount of radiation absorbed by the atmosphere.

Greenhouse heating of the atmosphere is dependent on atmospheric composition in several ways. First, water vapor is dominant over a wide wavelength interval, although in much of this region (8–18 μm) it is not optically thick. Because water vapor at high concentrations condenses to liquid drops or solidifies to ice, changes in water vapor concentration will not alter the thermal balance except through the formation of clouds. Yet atmospheric heat loss into space depends critically on the abundance of water; even water in the high stratosphere is significant. Second, carbon dioxide fills a large part of the water window, and current carbon dioxide abundances are enough to make the 12.5–18-μm region optically thick. Increasing atmospheric carbon dioxide abundances will alter greenhouse heating by absorption in the 10-μm bands and by making the 15-μm region even less transparent. Finally, a number of minor constituents such as methane, freons, and oxides of nitrogen have strong absorbing bands in the 8.5–12.5-μm window—even at small concentrations these substances can exert a major influence on the greenhouse effect.

As the atmospheric greenhouse warms the earth's surface, a number of complex feedback processes operate. A warmer surface leads to enhanced water evaporation with an increase in cloudiness. Clouds reflect a fraction of the incoming solar radiation, leading to a cooling effect. Clouds also trap surface radiation, which leads to warming, a phenomenon illustrated by the difference in temperature between cloudy and clear nights. The extent of snow and ice cover is lessened by a warmer surface which reduces the fraction of solar radiation reflected back into space, and leads to a warming feedback. Melting of snow and ice increases the water vapor concentration, thus increasing cloud cover that has both warming and cooling consequences. While such feedbacks are important, the atmospheric thermal regime is primarily controlled by the composition of the atmosphere and the associated radiative processes.

Calculating the combined radiation-trapping effect of a variety of molecular species is a complex task. The contributions of individual absorbers do not add linearly, in part because molecules differ greatly in their capacity to absorb radiation and because the regions that the species block off overlap. In rough terms, CO_2 currently accounts for 12% of the trapped radiation, but if all other absorbers were removed, CO_2 would trap three times as much energy. Similarly, clouds currently trap 14% of the radiation, but they would trap 50% of the currently absorbed radiation if all other absorbers were removed. The complexities of the radiative processes are further underlined by noting that the upper layers of the atmosphere leak relatively more radiation into space than they trap; water vapor and carbon dioxide are the principal radiators. Additional carbon dioxide leads to atmospheric cooling rather than warming at layers above 20 km.

Over the last decade, it has been recognized that a variety of substances have strong infrared absorption modes that lie in the window of transparency.[4] In some cases, the concentrations required to affect the radiative balance are minute compared with those of carbon dioxide, due to the strength of the absorption bands. Trace species that are capable of affecting the radiative balance include nitrous oxide (N_2O), methane (CH_4), and freons (CCl_3F, CCl_2F_2), as well as ozone. All of these trace substances are increasing in concentration due to agricultural and industrial activity, and these increases add to the blanketing capacity of the atmosphere.

CHANGES IN ATMOSPHERIC CARBON DIOXIDE CONCENTRATION IN HISTORICAL TIMES

Remarkably, carbon dioxide was the first constituent of the earth's atmosphere to be identified. Joseph Black published the discovery in 1754 in a University of Edinburgh thesis. By 1870, quantitative measurements developed which compare in precision with today's measurements. Interpretation of early observations is made difficult, not by inadequacies in analytical chemistry, but because they were not undertaken to measure changes in the composition of the atmosphere. Sampling for this purpose is complicated, owing to the extreme danger of contamination—for example, from the observer's breath. Although numerous observations of the CO_2 content of the atmosphere are reported in the literature during the period 1870–1910, their interpretation remains ambiguous. After about 1910, few reports are available, because the composition of the atmosphere was considered known and fixed, and analytical chemists pursued other interests.

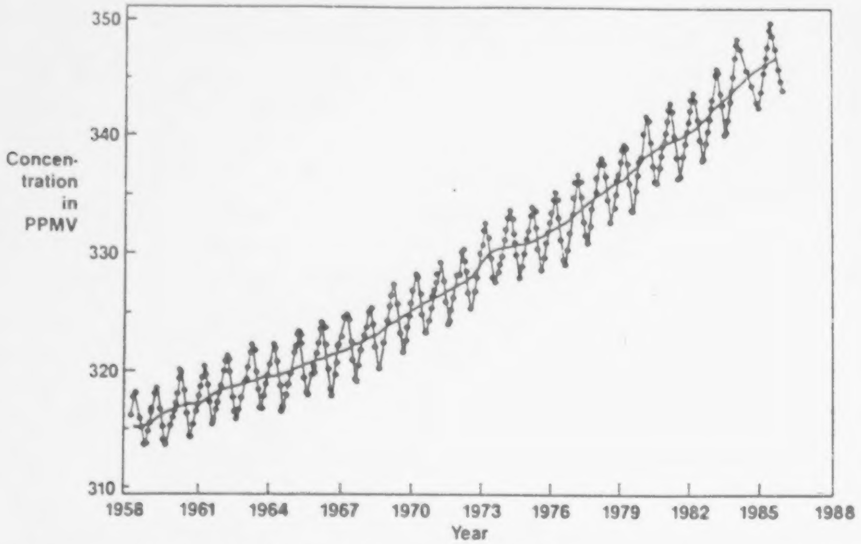


Figure 2. Atmospheric CO$_2$ in parts per million by volume (ppmv) concentrations at Mauna Loa Observatory, Hawaii. Measured amounts show seasonal fluctuations, primarily of biological origin, superimposed on an exponential growth. Source: C. Keeling, "Atmospheric CO$_2$ Concentration—Mauna Loa Observatory, Hawaii, 1958–1985," *U.S. Department of Energy Report No. NDP-001/R1* (Oak Ridge, TN: Carbon Dioxide Information Center, 1986).

The situation changed dramatically in 1958 when, at the suggestion of Roger Revelle, Charles Keeling of the Scripps Institution of Oceanography began a series of painstaking measurements of CO$_2$ concentration at a remote site in Hawaii, now the Mauna Loa Observatory. His observations, continued to the present, show an exponential growth of atmospheric carbon dioxide on which a periodic seasonal fluctuation is superimposed[5] (see Figure 2). The seasonal variation follows the biospheric uptake of CO$_2$ during the growing season and its discharge during winter. Keeling also established and maintained an observing regimen at the South Pole. The Antarctic observations show a similar exponential growth, but a more diminished seasonal variation (see Figure 3). Because the atmosphere at the South Pole is well removed from biological activity, the smaller seasonal fluctuations are expected. Keeling's observations have been duplicated at other stations in various parts of the world over shorter periods of time. In all sets of observations, the exponential increase is clear, though the amplitude of the seasonal terms varies with latitude. For example, a 20-year record taken from observations on a weather ship in the northeast Pacific (50°N, 145°W) shows greater seasonal fluctuations than those seen at Mauna Loa; the amplitude of these fluctuations reflects the strong seasonal dependence of the midlatitude, northern-hemisphere biological activity.[6]

The exponential growth in the change of atmospheric CO$_2$ concentration correlates with the release of CO$_2$ by the burning of oil, coal, gas, and wood. Since 1945, the injection of carbon into the atmosphere by fuel combustion appears to be exponential, with a slowing in growth following the 1973

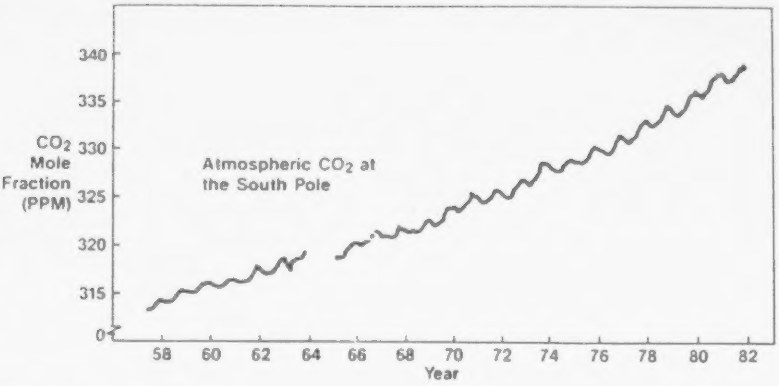


Figure 3. Trend in measured concentration shows the amplitude of seasonal fluctuations to be much less than at Mauna Loa because of the South Pole's remoteness from heavy biological activity. Source: C. D. Keeling, "The Global Carbon Cycle: What We Know and Could Know from Atmospheric, Biospheric, and Oceanic Observations," *Proceedings of the Carbon Dioxide Research Conference: Carbon Dioxide, Science and Consensus* Conference No. 820970 (Washington, D.C.: U.S. Department of Energy, 1983), pp. II.3–II.62.

explosion in energy prices (see Figure 4). In 1958, the increase in CO_2 concentration of the atmosphere, as determined from measurements at Mauna Loa, corresponded to an increase of carbon dioxide in the atmosphere of 4.4×10^9 metric tons; in 1981, the concentration change was equivalent to an increase of 10.3×10^9 metric tons to the atmospheric carbon dioxide content. Exponential fits to the Mauna Loa and South Pole data bracket the increase in carbon-based fuel use with the following *e*-fold times for carbon dioxide added to the atmosphere:

Mauna Loa	26.6 years
Fuels	23.9 years
South Pole	21.9 years

The corresponding *e*-folding time for total atmospheric carbon dioxide is 80 years.

Although the growth in atmospheric CO_2 parallels the release of carbon through energy use, the overall carbon budget is not well understood. The observed increase in atmospheric CO_2 accounts for only about half the carbon released through energy and industrial uses. Oceans are generally assumed to be a major sink for CO_2. Numerous models have been constructed to mimic ocean-wide diffusive and convective exchange processes, but the ocean's capacity to remove CO_2 from the atmosphere over time on the order of decades remains largely uncertain. The carbon balance mystery is deepened by inadequate data on the net contribution of biospheric processes to the burden of atmospheric carbon. Destruction of forest cover and cultivation of new land provides a source of atmospheric CO_2, but stronger growth in the many plants stimulated by increased CO_2 concentration should lead to greater biological productivity, and thus lead the biosphere to serve as a sink for CO_2. Both the sources and sinks associated with the biosphere

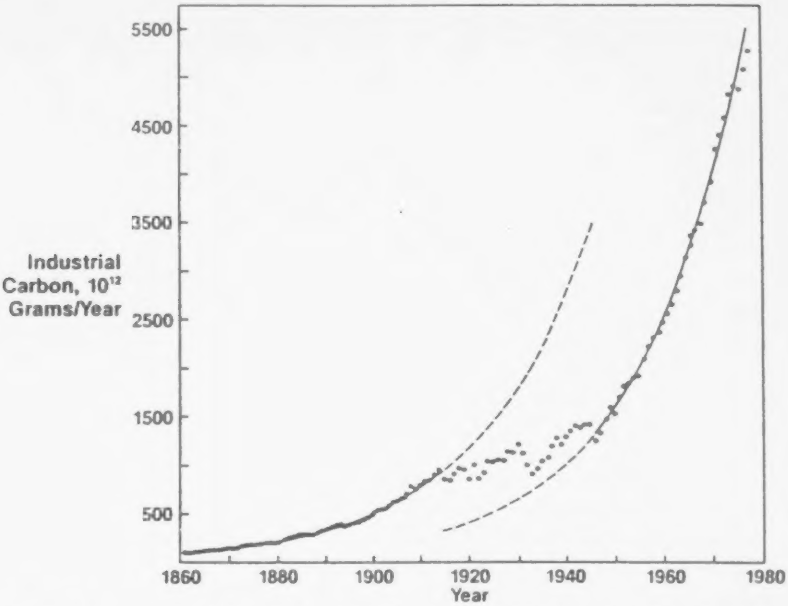


Figure 4. Anthropogenic CO_2 production. The rate of production of carbon dioxide by man's activities. Units are 10^{12} g yr^{-1}. The major deviations from exponential growth between 1914 and 1945 reflect the effects of the two World Wars and the worldwide economic chaos between the wars. Source: E. From and C. Keeling, "Reassessment of Late 19th Century Atmospheric Carbon Dioxide Variation in the Air of Western Europe and the British Isles Based on Unpublished Analysis of Contemporary Air Masses by C. S. Callendar," *Tellus*, 38B (1986): 87–105.

are large numbers, so that the net impact, being the difference of these large numbers, is most uncertain.

Estimates of future atmospheric carbon dioxide levels are clouded by questions regarding the overall carbon budget. A rough guess is provided by the observation that, historically, about half the fossil-fuel carbon placed in the atmosphere remains there. More refined estimates will require a better definition of the role of the oceans and biosphere in the carbon cycle. Disentangling the roles of the biosphere as a source and sink for carbon dioxide will require a far better carbon budget for the biosphere than is now available. In particular, the roles of soil erosion and of carbon sequestering in the deep ocean in determining the current carbon inventory of the biosphere are most uncertain. An alternative approach that will require patience and analytical chemical wizardry is the determination of long-term variations in oxygen concentration of the atmosphere.[7] Both the burning of carbon-based fuels and deforestation and erosion remove oxygen from the atmosphere through the formation of carbon dioxide. Because the rate of removal from burning of fuels is known, a determination of the oxygen budget could aid in determining the net contribution of the biosphere to the carbon cycle.

The concentration of CO_2 in the atmosphere was about 315 ppm by volume when Keeling began his observations in 1958. during the period 1958–1986, CO_2 concentration increased by about 30 ppm, or 9.5% in 28 years. Central to understanding the total impact of intensive agriculture and energy use on the present CO_2 concentration is to establish the concentration 100 years ago, when these activities were just beginning. There are a number of ways to obtain a preindustrial value. The first is to assume that conditions prevailing over the last 30 years held during the preceding 70. If one-half the carbon released by combustion remains in the atmosphere and all other sources and sinks are relatively constant, the concentration of CO_2 in the atmosphere in 1890 was about 293 ppm. Two ways of checking this value are available—analysis of air trapped in glaciers, and a careful reanalysis of the older observations.

When snow is transformed into ice during glacier growth, air is trapped in the intergrain spaces. The air remains in the airtight glacial ice as the glacier continues to grow. Chemical analysis of this air provides an estimate of the CO_2 content of the atmosphere at the time the air was encased. A number of difficulties lessen the value of such determinations. The time at which a particular layer of ice was laid down is difficult to estimate. The rate of snow accumulation affects the quantity of air that is trapped. The seasonal melting of snow may incorporate new air, leading to confusion. Despite these uncertainties, the values obtained from analysis of the most favorable samples indicate an atmospheric CO_2 concentration in 1890 of between 280 and 295 ppm.[8] These values are in general agreement with the value obtained by extrapolating current CO_2 concentration backward, assuming constant relative sources and sinks of CO_2.

Eric From and Charles Keeling[9] have carried out a detailed reexamination of early observations of CO_2 concentrations, particularly those made by Callendar, the discoverer of the significance of anthropogenic CO_2. Among the criteria From and Keeling used was whether early observations showed a seasonal cycle in accord with modern observations. The result of their analysis is that the mean annual concentration of atmospheric CO_2 circa 1880, in uncontaminated air at 50°N latitude, was 292 ppm. This value is consistent with backward extrapolation of current values, as well as estimates derived from glacial air samples.

Historical observations, coupled with extremely careful modern measurement, show that the CO_2 concentration of the atmosphere has increased from about 290 to 345 ppm in 100 years, or 19%. Future concentrations of CO_2 are difficult to estimate, because they depend on unknown energy use rates, mixtures of fuels, patterns of deforestation and agriculture, and uptake of CO_2 by the oceans and atmosphere. Uncertainties in future CO_2 levels due to uncertainties in the carbon cycle may be small if past behavior provides a reliable clue; if this is the case, about one-half of the CO_2 produced by fossil fuel combustion ends up in the atmosphere. There remains the difficult task of projecting energy use decades into the future if we are to determine the atmosphere of tomorrow and its associated climate.

TRENDS IN OTHER WARMING GASES

Historical trends of other anthropogenically produced gases, including methane, nitrous oxides, and ozone, are poorly known, in part because recognition of their significance to climate change has come only in the last decade. Freons present a different story; they are manufactured gases and came into major use only during the 1960s. Production data are readily available, except for eastern bloc countries and China, and, because freons are very long lived in the atmosphere, production data alone provide a good guide to their trends since introduction during the 1960s.

Anthropogenic sources of methane include direct emissions from the production and transportation of natural gas and from the burning of biomass. Cultivation of rice paddies and the raising of ruminant animals can also lead to increased methane production. Interpretation of the observed methane concentration is complicated in that a number of atmospheric chemical reactions involving methane and other constituents, such as carbon monoxide, can lead to increases or decreases in atmospheric methane concentration. Furthermore, emissions of carbon monoxide are increasing as the use of fossil fuels increases. Observations made over the past decade at a number of stations show that the CH_4 concentration is increasing at about 2% per year.[10] Whether the increase is due to greater emissions or heightened removal of constituents in the atmosphere that would otherwise react with methane is not clear. As in the case of carbon dioxide, data on past methane concentrations can be obtained from the analysis of trapped air in glaciers. These data suggest a long-term exponential growth with an exponential doubling time of 46 years (see Figure 5). Given the large uncertainties in interpretation of the air-bubble data, the close fit of observation with the exponential fit should be viewed with some skepticism, particularly because the sources and sinks for methane are not well understood.

Although the overall residence time of methane in the atmosphere is relatively short (about six years), nitrous oxide is much less reactive and has a

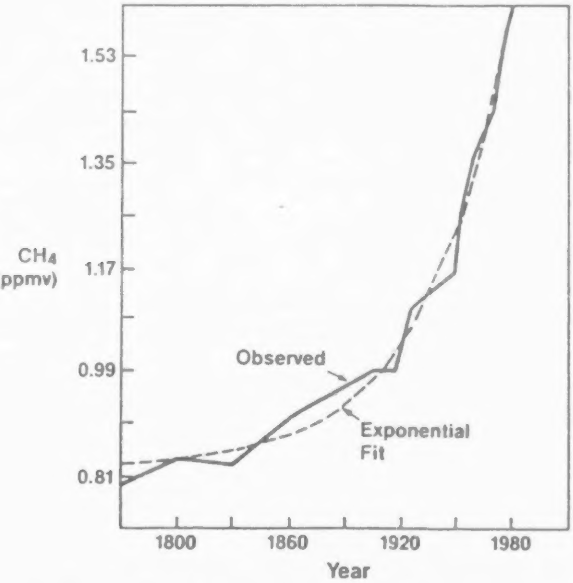


Figure 5. Estimated variation of atmospheric methane concentrations. Data prior to 1960 taken from measurements of methane contained within air bubbles in ice cores. Source: B. Stauffer, G. Fischer, A. Nefter, and H. Oeschinger, "Increase of Atmospheric Methane Recorded in Antarctic Ice Core," *Science*, 229 (1985): 1386–1388.

residence time of over 100 years. The current annual rate of increase of N_2O is estimated at 0.2% per year.[11] This value is based on sparse observations; historical data are not available. A number of processes add N_2O to the atmosphere. Combustion of fuel produces N_2O, as does the breakdown of ammonia used as a fertilizer. Disposal of human and animal waste strongly stimulate nitrification, and refuse disposal is another source of atmospheric N_2O.

Freons came into major use during the 1960s and initially showed a high 10%-15%-per-year growth. Due to the imposition of environmentally based regulation and to the downturn in economic growth, the rate of freon use slowed during the late 1970s and early 1980s, but has resumed more recently.[12] Most recent data indicate a growth rate for $CFCl_3$ of 9.0 parts per trillion (ppt) per year and for CF_2Cl_2 of 15.3 ppt per year.[13] These values correspond to percentage growth rates for both $CFCl_3$ and CF_2Cl_2 of 5.1% per year. The observed atmospheric concentrations and growth rates are in good agreement with published production data.[14]

A variety of observations shows that the tropospheric concentration of ozone is increasing, even though the stratospheric concentration may be decreasing as a result of complex chemical reactions with freons stimulated by ultraviolet radiation. Although the total amount of ozone in the troposphere is small compared with stratospheric ozone, it is important in considering the energy balance of the atmosphere. At the lower levels of the atmosphere, ozone is at higher pressures, and its absorption of outgoing infrared radiation is much more effective than higher level ozone. Measurements from a rural site on an island in the Baltic show an increase in ozone of about 60% since the 1950s.[15] Similar trends have been observed at stations in the Alps, North America, and Japan, though local atmospheric conditions complicate interpretation of the data.[16]

As in the case of methane and nitrous oxide, the sources and sinks of ozone are not thoroughly understood. Ozone forms photochemically in urban smog but can also form in rural atmospheres if hydrocarbons are present. Free hydroxyl radical (HO) is a principal sink for ozone, but HO may be taken up by methane and carbon monoxide, with which it also reacts. Increasing concentrations of CH_4 and CO will lead to increased tropospheric ozone. A principal source of carbon monoxide is the automobile. Increased automobile traffic leads to increased levels of hydrocarbons and nitrogen oxides—sources of ozone—and of carbon monoxide, which is a sink for hydroxyl. The combination of higher source concentrations and lower sink (hydroxyl) concentration leads to higher ozone levels and increased atmospheric warming.

Although the importance of methane, freons, nitrous oxide, and ozone in producing a greenhouse effect is well established, their past and future concentrations are much less certain. All are the result, either directly or indirectly, of energy use and industrial activity. Thus, all of these radiatively active species can be expected to increase significantly over the next 50 years.

MODELS OF CLIMATE CHANGE DUE TO GREENHOUSE GASES

The task of predicting changes in climate is extremely complex. Given the relative stability of climate, evidenced by the observed slow rate of climate change over geologic time, it is tempting to seek a past climate that would provide an analogue to present and future climates. Increasingly detailed data are available on conditions that prevailed during the Holocene climatic optimum (5000 to 6000 years B.P.), the last major interglacial period (about 125,000 years B.P.), and the Pliocene warming (3 to 4 million years B.P.). During these intervals, the mean temperature was warmer than today by about 1 °C, 2 °C, and 3–4 °C, respectively. These times are poor analogues to future climatic change, however. Past changes took place slowly, on time scales of at least thousands of years; their cause is not known. Today, changes in the composition of the atmosphere are taking place in decades, the basic radiative characteristics of present constituents are nonlinear, and changes in composition are taking place at an exponential rate. Although past climates may provide guidance as to the possible future evolution of warm periods, they yield less information as to current trends. An alternative to extrapolating from historical climates is to construct artificial ones from mathematical models.

Over the years, a hierarchy of climate models has been developed to predict changes in climate. At one end of the scale are energy-balance models based on conservation of energy, which in their simplest form treat the entire earth's surface as having a single temperature. Their advantage is their simplicity; the only equation that enters is that of conservation of energy values, unknown quantities need not be assumed, and the calculation does not require a computer. The disadvantage of such energy-balance models is that only average temperature changes are predicted; this failing must be weighed against the advantages of parsimony of assumptions and simplicity of calculations. At the other end of the scale of complexity are the global circulation models (GCM). These are three-dimensional representations of the atmosphere that explicitly include equations for conservation of mass, water vapor, energy, and zonal and meridional components of momentum. In their most detailed form, GCMs are based on a 500-km grid size in the numerical approximation to horizontal motions, with up to nine layers in the vertical direction. As a result, on the order of 20,000 grid points are required in approximating the continuous atmosphere over the earth's surface. In total, the calculation requires the treatment of about 200,000 equations, with each equation requiring extensive calculations. The calculation of the evolution, over time, of this large set of equations strains the largest available computers, particularly when careful attention is paid to delicate issues of numerical stability of the finite difference approximation to the underlying partial differential equations.

Comprehensive three-dimensional models are designed to provide estimates of those parameters of climate change most critical to society—the regional, seasonal, and diurnal distribution of temperature, soil moisture, and surface runoff. This task is complicated by the requirement that valid approximations be developed for the many processes taking place over the time and space scales of interest. For example, there is a need to represent clouds and cloud systems which typically have dimensions of one to ten kilometers, much less than the resolving power of the numerical grid of 500 km. Major difficulties arise in parametrizing cloud coverage and cloud heights, because these quantities vary on scales less than the numerical resolution. Because clouds are important in calculating the distribution of radiative energy, the manner in which the approximations are made is critical, and various climate modeling groups use somewhat different approaches.

Similar difficulties in parametrization arise in treating soil moisture, air-sea interaction, topography, biological activity, and other important variables.

Among models of complexity intermediate to the energy balance and GCMs are the radiative-convective models (RCM).[17] These treat the vertical structure of a global average atmosphere, but to not deal with horizontal motions. RCMs are particularly well suited to a detailed evaluation of the radiative effects of CO_2, trace gases, and aerosols, as well as the chemical reactions among radiatively active substances.

A conventional means of comparing models is to calculate the average surface temperature that would result from doubling the atmospheric CO_2 concentration from 330 to 660 ppm. Early estimates made during the late 1960s predicted that a doubled CO_2 content should raise the average temperature 1.5 to 3 °C.[18] More than 100 independent estimates of average surface temperature increase have since been made using energy balance, RCMs and GCMs. Almost all of these estimates lie in the range 1.5–4.5 °C, with values near 3 °C tending to be favored.[19]

Intercomparisons of GCM simulations of CO_2-induced climate change show that although there is general agreement as to the surface temperature change, there is much less agreement in the geographical distribution of temperature changes, and sometimes large disagreement on geographical distribution of soil moisture and runoff. This state of affairs is not surprising in that the calculation of temperature depends primarily on energy conservation, and all models incorporate this basic feature. Geographic distributions of various quantities, particularly those involving precipitation, will sensitively depend on the details of the parametrization of those quantities that are poorly understood or inadequately resolved in the numerical approximations, or both.

The large heat-retaining capacity of the oceans coupled with the mixing processes in their upper layers are the main factors providing thermal inertia to the climate system. This thermal inertia slows down climate change due to anthropogenic changes in atmospheric composition. GCMs that include atmosphere-ocean coupling can be used to calculate the delay of the equilibrium response of the atmosphere to changes in atmospheric composition. Results from available models suggest that thermal storage and mixing in the ocean reservoirs cause a lag in the warming of 10 to 20 years. If an exponential change of atmospheric CO_2 composition with a doubling time of 20 years leads to an equilibrium warming of 1 °C, then the observed response would only be 0.7 ± 0.2 °C.[20] The large uncertainty arises because of incomplete knowledge of the formation of bottom waters and of the mixing processes in the wind-stirred upper layers of the oceans, particularly the Arctic and Antarctic pumps involving thermohaline circulations.

Over the past 100 years, the carbon dioxide content has increased by about 20%. A range of model calculations suggests that the corresponding equilibrium temperature rise should be 0.5 to 1.0 °C. If this is corrected for the effects of the thermal inertia of the oceans, the changing composition of the atmosphere should have produced a warming of 0.35 to 0.7 °C, superimposed on the natural fluctuations of the atmosphere. Because natural variations associated with El Niño and volcanic eruptions bring about short-term changes on the order of a few tenths of a degree, the roughly half-degree increase of the longer-term trend must be extracted by careful statistical analysis.

OBSERVED CLIMATE CHANGES

In addition to noting the anthropogenic warming, Callendar[21] attempted to estimate the change in climate he observed. As interest in the subject has increased, larger computer-based data sets have been developed. The principal problem in analyzing the data is one of sampling. Data are highly biased toward land in the northern hemisphere. Because oceans cover more than 70% of the earth's surface, this bias is large. Many land-based observing stations are located near urban sites. This location itself introduces a further bias, because, as the urban region grows, more energy is consumed, and there is a local warming trend. Inconsistencies in data collection stem from changes in both observing instruments and calibration practices. Observing stations have been relocated, and the shelter used to house the thermometer may have been altered. These are just a few of the difficulties that must be overcome in order to construct a homogeneous data set. Although all of these considerations are important, the principal deficiency in the past has been the lack of data over the oceans.

Detailed analyses of land-based observations have been carefully examined to detect and correct for nonclimate errors that result from station shifts, urban development, and changes in instrumentation.[22] Several researchers have attempted the daunting task of using sea surface temperatures (SST) and marine air temperatures (MAT) recorded by ships at sea to obtain ocean temperature estimates.[23] For MAT there are problems, including a great diversity of instruments and practices, as well as varying placement of the thermometers on ships. SST have been determined from bucket measurements and later from water intake measurements, after the conversion from sail to steam. Attempts have been made to calibrate the SST and MAT observations by first carrying out a correlation of MAT with nearby land for 15 regions of the world.[24] The corrected MAT for various time periods are then used to calibrate the SST. The large number of observations includes a British data set of 46 million SST observations,[25] and the Comprehensive Ocean Atmosphere Data Set of the National Oceanic and Atmospheric Administration, comprising some 63 million SST observations.[26]

The curve in Figure 6 shows a long-term warming trend. The magnitude of the warming agrees with theory; it is about 0.5 °C over the last 100 years. Confirmatory evidence for the warming trend, derived from a statistical treatment of vast numbers of observations of varying quality, has been obtained from measurements of a totally different kind. A. Lachenbruch and V. Marshall[27] determined the variation of temperature with depth in the permafrost in a number of wells at each of three sites in northernmost Alaska: Barrow, Cape Thompson, and Prudhoe Bay. Because of the low thermal diffusivity of rock, temperatures beneath the ground surface represent a systematic running mean of the recent temperature history of the surface; the low thermal diffusivity damps out the high-frequency variations in air temperature. The permafrost prevents circulating ground waters from perturbing the thermal regime established by surface temperature. The deeper the temperature measurement, the farther back in time is the interval of surface temperature that it represents. The subsurface permafrost thus "remembers" major shifts in averaged surface temperature; measurements to a few hundred meters record the temperature history of the past few centuries.

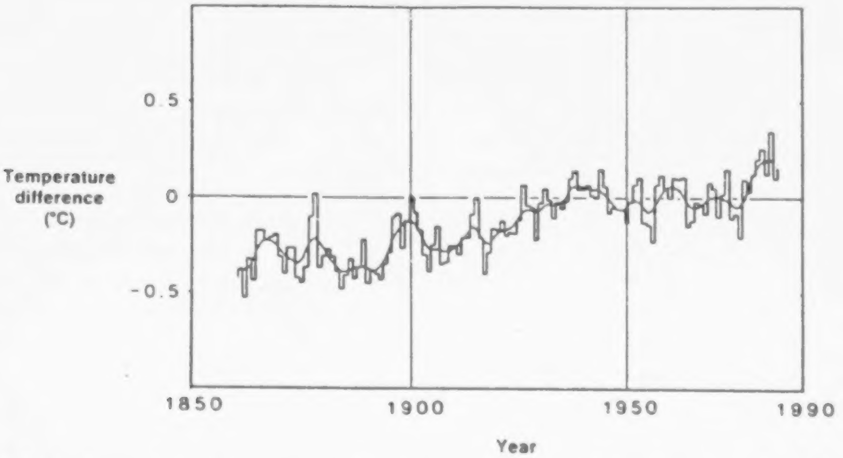


Figure 6. Annual mean temperature variations since 1861. Source: P. Jones, T. Wigley, and P. Wright, "Global Temperature Variation Between 1861 and 1984," *Nature*, 322 (1986): 430–434.

Lachenbruch and Marshall have shown that the surface temperature has increased 2 to 4 degrees Celsius during the last few decades to a century. Their conclusion is in accord with theory and models that predict a global average warming of 0.5 to 1.0 °C, if the latitude dependence of incoming radiation is taken into account—at the Arctic Circle, the increase is predicted to be higher by a factor of 6 to 8 over the global average.

In view of the heightened interest in long-term climatic change, the question naturally arises as to whether this trend would have been noticed if theory had not predicted that it should be there. I was convinced of the warming long before the detailed analysis of the records were available. I had observed that the snouts of the glaciers on the Alps on the South Island of New Zealand had moved from sea level to high up the mountain between 1900 and the present. New Zealand, having a relatively isolated geographical setting in the ocean, was more likely to capture longer-term trends in climate than glaciers in more continental regions. Yet glaciers, even on an isolated island, may not well serve as a surrogate for overall climate change. Because theoretical predictions of a one-half-degree warming preceded the statistical analysis of historical observation, critics undoubtedly will question the reality of the derived warming. Nevertheless, the statistical base for the inference is strong, and the independent confirmation from the Arctic may prove persuasive.

The record of the warming trend shown in Figure 6 has several interesting features. The three warmest years were 1980, 1981, and 1983. Five of the nine warmest years in the 134-year record occurred after 1978. Puzzles remain, however. For the 40-year period between the mid-1930s and the mid-1970s, the average temperature remained approximately stable at a time the exponential change in atmospheric composition should have produced an increased rate of warming. The increase in temperature between 1905 and about 1930 is high when compared to the expected increase. Thus, although the overall change in temperature is in the right direction and of the correct magnitude, a number of features of the observed warming are inconsistent with those expected from the greenhouse effect alone.

FUTURE GREENHOUSE WARMING

Projections of future warming are uncertain, because future levels of use of carbon-based fuels are not known. The contemporary budgets of methane and nitrous oxides are not known, so projections of the contribution of these gases to future climatic shifts are even more uncertain than that of CO_2. However, over a relatively short interval of 50 years, 1980 to 2030, limits can be placed on expected climate variations, on the assumption that there will be no radical shifts in the world's agricultural-industrial base. V. Ramanathan and colleagues, using a radiative-convective model, have calculated an equilibrium warming of 1.5 °C between 1980 and 2030, assuming a stable projection of current energy use.[28] A little less than half of the projected increase is due to CO_2; the remaining increase is due to the other radiatively active gases. If the thermal inertia estimate of about 0.7 of the theoretical warming holds, the expected warming during the next 50 years is about 1 °C, or twice that shown for the interval 1880 to 1980. The total warming of 1.5 °C over the 150-year period ending in 2030 would be equal to or larger than that estimated as taking place during the Holocene, 5000 to 6000 years ago.

Using the simpler energy budget model, I have calculated a comparable temperature change.[29] The assumed increases in the warming gases are shown in Table 1. Also included is carbon monoxide, which is an infrared absorber, but whose concentration influences the abundance of methane and ozone. The calculated equilibrium surface warming is 1.8 to 2.2°C, as indicated in Table 2. This corresponds to an actual warming of 1.3 to 1.5 °C, if current estimates of the thermal lag of the oceans are appropriate. The contribution to the warming of species other than CO_2 is 80 to 120% of the CO_2 warming, with ozone and methane being the principal other contributors. The major difference between the two preceeding sets of estimates, other than the model basis, is that Ramanathan et al. anticipate a significantly greater contribution of freons to the warming (0.44 °C) and lower contributions from ozone and methane. The lower contribution from ozone is a product of the Ramanathan et al. estimate of only a 12.5% growth in 50 years, which seems low when compared with recent trends.

Although the magnitude of future sources and sinks of radiatively active substances other than CO_2 is uncertain, it appears that the contribution of these gases to future warming can be as great or greater than that due to CO_2. The average global temperature in the year 2030 should be 1 to 1.5 °C warmer than today. The climate in this regime will differ markedly from that to which we have become accustomed.

CONCLUSIONS

Despite the many uncertainties in future energy use, carbon cycle evolution, and production of trace gases, it appears highly probable that over the next 50 years anthropogenic activities will warm the earth's surface by 1 to 1.5°C. This warming will be beyond the half-degree warming of the last 100 years.

Table 1. Changes in concentration of radiative active gases for the period 1980–2030.

Species	Residence time (years)	1980 mixing ratio (ppbv)	Estimated 2030 mixing ratio (ppbv)
CO_2	2	340×10^3	450×10^3
N_2O	120	300	350–450
CH_4	7–8	1650	2500–3000
CCl_2F_2	110	0.30	0.6–1.2
CCl_3F	65	0.18	0.5–1.0
O_3 (Troposphere)	0.1–0.3	20–70	30–100
CO	0.3	90	100–200

These changes are larger than those that can be anticipated from natural variations and are of the same order or larger than those associated with the Holocene warming 6000 years ago. If GCMs and previous climates are any guide, it is likely that the effects will be noted first at high latitudes; observed variations over the past century support this conclusion.

Although there is wide agreement among climate modelers as to future warming trends, there is far less agreement as to future regional patterns of climate. On land, there will be poleward and upward shifts of temperature conditions. So far as agriculture is concerned, there would be longer growing seasons in higher latitudes. In many regions, however, climate conditions best suited for grain production would move into formerly glaciated areas with thin, nutrient-stripped soils. There will be a tendency toward lower precipitation and soil moisture in the midcontinent regions of North America and Eurasia. The higher concentration of atmospheric carbon dioxide would probably favor photosynthesis and increased agricultural production. The balance of advantage and disadvantage would be local or regional. Yet it seems likely that production in the major existing grain-growing regions of the world, particularly Canada, United States, Soviet Union, and China would, on balance, be adversely affected. In all cases, it would take considerable time, effort, and investment to adjust to new circumstances, even in areas where they would be on net favorable.

Changes in climate will alter, as well as manage, natural ecosystems. For example, higher temperatures usually result in an increase in the number

Table 2. Surface warming due to change in atmospheric composition, 1980–2030 (see Table 1).

Component	ΔT_S in °C
CO_2	1.0
O_3 (Troposphere)	0.2–0.4
CH_4	0.3–0.4
N_2O	0.2
$CFCl_3$ and CF_2Cl_2	0.1–0.2
Total	1.8–2.2

and species of insects. Farmers would face a different and possibly even greater problem in pest control. Changes in wind patterns lead to alteration in ocean currents, which would affect the supply of nutrients and thus the location of the world's fish.

At present, sea level is gradually rising at the rate of a few centimeters per century. A global warming accentuated at the poles could lead to substantial melting of glacial ice, increasing the rate of sea-level rise. The rate of expected rise is not known, though the grounded ice sheet in West Antarctica has long been suspected of instability; a meter's rise in the next century would be consistent with current change, but a greater increase cannot be excluded. A several meter rise would endanger most of the world's great cities and much of the present fertile agricultural land.

A most important consideration is the future variance in climatic condition. A continually changing thermal regime for the atmosphere may lead to increasing oscillations analogous with other dynamical systems. Global warming could be accompanied by greater climate variability, leading to a higher frequency of extremes such as floods, droughts, and storms. The economic effects of increased atmospheric variance may well exceed those of shifting geographic climate patterns.

Much current thinking about the greenhouse effect assumes that society will adapt incrementally to change, even if the changes involve heightened sea level and droughts in the "food basket" areas of North America and Eurasia. These assumptions are not convincing. Infrastructures of society such as water supplies, transportation nets, and land-use patterns have evolved over centuries in response to prevailing climate. Over decades, significant changes in climate will exert profound disruptive forces on the balance of infrastructures. Of central interest will be the adaptability of the world's several political-legal-economic systems. The prevailing market economies in much of the world adjust to alterations in supply and demand through adjustments in price. The intangibles of climate change due to the burning of fossil fuels are not readily quantified in conventional market terms; they are one of the externalities with which markets find so hard to deal.

Rapidity of climate change depends on the world's future use of fuels. Coal, the most geologically abundant fuel, produces about 80% more carbon dioxide per unit of primary thermal energy delivered than does natural gas; oil produces 44% more than does gas. Burning coal also leads to a significantly greater production of other greenhouse gases, such as ozone and oxides of nitrogen, than do other carbon-based fuels. Yet current price mechanisms do not include the long-term costs associated with climate change of burning coal rather than its substitutes. In the United States over the past 10 years, the use of coal has steadily increased, even as knowledge of the greenhouse effect has spread.

If predictable climate changes become unacceptable, a move away from carbon-fuel based economies, whether stimulated by market forces or government intervention, is one alternative. Nuclear power is a candidate energy substitute, but this alternative causes far greater fear among much of the world's population than does climate change. Whether this fear is justified is irrelevant; the perception of danger from the operation of nuclear power plants and storage of waste is real.

Climate is a condition of life. All the world's people are subject to climate change. When climate changes, societies must adapt. No single country will be spared, though the northern countries may be subjected to more rapid change than those in the tropics. Until recently, most of those who are required to think forward—farmers, economists, planners, and politicians—were content to rely on historical records or linear extrapolation. With the progress in the scientific understanding of the greenhouse effect will come the recognition that problems of climate change should receive serious attention and may require unprecedented international concordance.

Conservative alternatives to that of blind belief in incremental adjustment are preparation of the way for alternative energy sources, including nuclear and solar energy,[30] as well as increasing overall energy efficiency. Although climate change may be acceptable in the short term, it is not clear that it will be in the longer term.

GORDON J. MacDONALD is Vice President and Chief Scientist of The MITRE Corporation, McLean, VA.

NOTES

1. H. Lamb, *Climate, History, and the Modern World* (London: Methuen, 1982).
2. J. Tyndale, "Philadelphia Magazine," *Journal of Science*, 22 (1861): 169–194, 273–285.
3. G. Callendar, "Temperature Fluctuation and Trends Over the Earth," *Quarterly Journal of the Royal Meterological Society*, 87 (1961): 1–12.
4. V. Ramanathan, "Greenhouse Effect due to Chlorofluorocarbons: Climate Implications," *Science*, 190 (1975): 50–51; J. Chamberlain, H. Foley, G. MacDonald, and M. Ruderman, "Climate Effects of Minor Atmospheric Constituents," in W. Clarke, Ed., *Carbon Dioxide Review: 1982* (Oxford University Press, 1982), pp. 255–277.
5. C. Keeling, "Atmospheric CO_2 Concentration, Mauna Loa Observatory, Hawaii, 1958–1983," U.S. Department of Energy Report No. NDP-001 (Oak Ridge, TN: Carbon Dioxide Information Center, 1984).
6. C. Keeling, T. Whorf, C. Wong, and R. Bellagay, "The Concentration of Atmospheric Carbon Dioxide at Ocean Weather Station P from 1969 to 1981," *Journal of Geophysical Research*, 90 (1985): 10511–10528.
7. G. MacDonald, *The Long-Term Impacts of Increasing Atmospheric Carbon Dioxide Levels* (Cambridge, MA: Ballinger, 1982).
8. D. Raynaud and J. Barrola, "An Antarctic Ice Core Reveals Atmospheric CO_2 Variations Over the Past Few Centuries," *Nature*, 315 (1985): 309–311.
9. E. From and C. Keeling, "Reassessment of Late 19th Century Atmospheric Carbon Dioxide Variation in the Air of Western Europe and the British Isles Based on Unpublished Analysis of Contemporary Air Masses by C. S. Callendar," *Tellus*, 38B (1986): 87–105.
10. M. Khalil and R. Rasmussen, "Sources, Sinks, and Seasonal Cycles of Atmospheric Methane," *Journal of Geophysical Research*, 88 (1983): 5131–5141; M. Khalil and R. Rasmussen, "Causes of Increasing Atmospheric Methane: Depletion of Hydroxyl Radical and the Rise of Emissions," *Atmospheric Environment*, 19 (1985): 397–407.
11. R. Weiss, "The Temporal and Spatial Distribution of Tropospheric Nitrous Oxide," *Journal of Geophysical Research*, 86 (1981): 7185–7196.
12. D. Cunnold, R. Prinn, R. Rasmussen, P. Simmonds, F. Alyea, C. Cardelino, A. Crawford, P. Fraser, and R. Rosen, "The Atmospheric Lifetime Experiment: 3,

Lifetime Methodology and Application to Three Years of $CFCl_3$ Data," *Journal of Geophysical Research*, 88 (1983a): 8379–8400; D. Cunnold, R. Prinn, R. Rasmussen, P. Simmonds, F. Alyea, C. Cardelino, and A. Crawford, "The Atmospheric Lifetime Experiment: 4. Results for CF_2Cl_2 Based on Three Years Data," *Journal of Geophysical Research*, 88 (1983b): 8401–8414.

13. D. Cunnold, R. Prinn, R. Rasmussen, P. Simmonds, F. Alyea, C. Cardelino, A. Crawford, P. Fraser, and R. Rosen, "Atmospheric Lifetime and Annual Release Estimates for $CFCl_3$ and CF_2Cl_2 from Five Years of ALE Data," *Journal of Geophysical Research*, 91 (1986): 10797–10817.

14. Ibid.

15. W. Warmbt, "Results of Long-term Measurement of Near Surface Ozone in the G.D.R.," *Zeitschrift für Meteorologic*, 29 (1979): 24–31.

16. J. Logan, "Tropospheric Ozone: Seasonal Behavior, Trends and Anthropogenic Influence," *Journal of Geophysical Research*, 90 (1985): 10463–10482.

17. V. Ramanathan, and C. Coakley, "Climate Modeling Through Radiative-Convective Models," *Reviews of Geophysics and Space Physics*, 16 (1978): 465–489.

18. S. Manabe and R. Wetherald, "Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity," *Journal of the Atmospheric Sciences*, 24 (1967): 241–259.

19. M. Schlesinger and J. Mitchell, "Model Prediction of the Equilibrium Climatic Response to Increased Carbon Dioxide," in M. MacCracken and F. Luther, Eds., *The Potential Climate Effects of Increasing Carbon Dioxide*, DOE/ER-0237 (Washington, DC: U.S. Department of Energy, 1985).

20. M. Hoffert and B. Flannery, "Model Projections of the Time-Dependent Response to Increasing Carbon Dioxide," in M. MacCracken and F. Luther, Eds., *The Potential Climate Effects of Increasing Carbon Dioxide*, DOE/ER-0237 (Washington, DC: U.S. Department of Energy, 1985).

21. G. Callendar, "The Artificial Production of Carbon Dioxide and its Influence on Temperature," *Quarterly Journal of the Royal Meteorological Society*, 64 (1938): 223–237; G. Callendar, "Can Carbon Dioxide Influence Climate?" *Weather*, 4 (1949): 310–314; Callendar, op. cit., 1961.

22. P. Jones, T. Wigley, and P. Kelly, "Variations in Surface Air Temperatures: Part 1. Northern Hemisphere 1881–1980," *Monthly Weather Review*, 110 (1982): 59–70; P. Jones, S. Raper, R. Bradley, H. Diaz, P. Kelly, and T. Wigley, "Northern Hemisphere Surface Air Temperature Variations 1851–1984," *Journal of Climate and Applied Meteorology*, 25 (1986): 161–179.

23. C. Folland, D. Parker, and F. Kates, "Worldwide Marine Temperature Fluctuation 1856–1981," *Nature*, 310 (1984): 670–673; P. Jones, T. Wigley, and P. Wright, "Global Temperature Variation Between 1861 and 1984," *Nature*, 322 (1986b): 430–434.

24. Ibid.

25. Folland *et al.*, *op. cit.*

26. Jones *et al.*, *op. cit.*, 1986b.

27. A. Lachenbruch and V. Marshall, "Changing Climate: Geothermal Evidence from Permafrost in the Alaskan Arctic," *Science*, 234 (1986): 689–696.

28. V. Ramanathan, R. Cicerone, H. Singh, and J. Kiehl, "Trace Gas Trends and Their Potential Role in Climate Change," *Journal of Geophysical Research*, 90 (1985): 5547–5566.

29. G. MacDonald, *Climate Change and Acid Rain*, MP8600010 (McLean, VA: The MITRE Corporation, 1985).

30. Burning wood or other sources of biomass, despite their widely advertised virtues, only add to the greenhouse gas burden.

The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment

V. RAMANATHAN

Since the dawn of the industrial era, the atmospheric concentrations of several radiatively active gases have been increasing as a result of human activities. The radiative heating from this inadvertent experiment has driven the climate system out of equilibrium with the incoming solar energy. According to the greenhouse theory of climate change, the climate system will be restored to equilibrium by a warming of the surface-troposphere system and a cooling of the stratosphere. The predicted changes, during the next few decades, could far exceed natural climate variations in historical times. Hence, the greenhouse theory of climate change has reached the crucial stage of verification. Surface warming as large as that predicted by models would be unprecedented during an interglacial period such as the present. The theory, its scope for verification, and the emerging complexities of the climate feedback mechanisms are discussed.

IN 1827, THE PHYSICIST-MATHEMATICIAN JEAN-BAPTISTE Fourier (*1*, p. 569) stated aptly: "The question of global temperatures, one of the most important and most difficult in all natural philosophy, is composed of rather diverse elements which should be considered under one general viewpoint" (translation from French). A century and a half later, several national and international research groups (*2*) are studying the diverse elements of the climate system. The fundamental motivation for the surge of interest in climate studies is the growing scientific concern that human activities may significantly alter the world's climate, if they have not already done so. The sources for this concern are the observed changes in the atmospheric gaseous composition. Recent advances in the observational area of in situ gas sampling (*3*) have shown that the concentrations of several atmospheric trace gases have increased significantly all over the globe during the last decade (Table 1). Chemical analyses of gases trapped in ice cores reveal that the increase began during the 19th century (Table 1). Model studies of the chemical balance of the atmosphere, the ocean, and the biosphere provide compelling arguments for attributing the observed increases to human activities (*2*, *4*).

The gases listed in Table 1 absorb infrared (IR) radiation (also known as terrestrial or thermal radiation) emitted by the relatively warmer surface and emit radiation to space at the colder atmospheric temperatures, leading to a net trapping of IR energy within the atmosphere (the greenhouse effect). The long-term climate is governed by a balance between the absorbed solar radiation and the emitted IR. When there is enhanced IR trapping, for example, as a result of an increase in the concentrations of gases shown in Table 1, excess energy is suddenly available to drive the climate system. The result, according to the theory, is a "vigorous" climate system, that is, a warmer globe with a more active hydrological cycle. The earth warms until the excess IR energy trapped by the greenhouse gases is radiated to space as IR emission. Because of the nonlinear interactions between the atmosphere, the cryosphere (ice and snow), the oceans, and the land, the predicted warming is not uniform but varies significantly with latitude, longitude, altitude, and season. The temperature and pressure gradients that result from the nonuniform warming patterns can alter the general circulation of the atmosphere and the oceans.

The greenhouse effect of the atmosphere was pointed out, perhaps for the first time, by Fourier (*1*), who also suggested that human activity can modify climate. The formal foundation for the greenhouse theory of climate change was laid in 1896 by Arrhenius

---

The author is at the Department of the Geophysical Sciences, University of Chicago, Chicago, IL 60637.

Table 1. Trace gas concentrations and trends: observed and projected. The concentrations are from (*4*); the decadal trends for 1975 to 1985, showing the percentage of increase in concentrations, are from (*3*).

Gas	Concentrations		Observed trends for 1975–1985 (%)	Mid-21st century
	Pre-1850	1985		
CO_2	275 ppmv	345 ppmv	4.6	400–600 ppmv
CH_4	0.7 ppmv	1.7 ppmv	11.0	2.1–4 ppmv
N_2O	0.285 ppmv	0.304 ppmv	3.5	0.35–0.45 ppmv
CFC-11	0	0.22 ppbv	103.0	0.7–3.0 ppbv
CFC-12	0	0.38 ppbv	101.0	2.0–4.8 ppbv
Tropospheric O_3* (below 12 km)		10–100 ppbv		
CH_3CCl_3	0	0.13 ppbv	155.0	
CCl_4	0	0.12 ppbv	24.0	

*Values (below 9 km) for before 1850 are 0 to 25% less than present-day; values (below 12 km) for mid-21st century are 15 to 50% higher.

(5), who dealt with the climatic effects of changes in atmospheric CO_2. On the basis of his finding that a doubling of atmospheric CO_2 would warm the globe by 5 K, Arrhenius concluded that past glacial epochs may have occurred largely because of a reduction in atmospheric CO_2. This conclusion is rapidly gaining favor because analyses of air trapped in glacier ice have revealed that CO_2 concentrations in the past fluctuated from about 270 to 300 parts per million by volume (ppmv) during interglacial periods to about 180 ppmv during periods of glacial advance (*6*). Finally, Callendar (*7*) concluded in the late 1930s that human activities were causing an increase in atmospheric CO_2, and that this increase could initiate a global warming. In 1967, Manabe and Wetherald (*8*) provided quantitative results for the CO_2-induced global warming, on the basis of a model that treated the concepts of global energy balance and radiative-convective equilibrium (*9*). The theory of climate change involving CO_2 variations is now viewed as one of the major mechanisms for understanding climate variations of the past, including the Archean (*10*), the Cretaceous (*10*), and the ice ages of the Pleistocene (*6*).

The importance of the other trace gases was not recognized until the last decade when it was found that the addition of one molecule of CFC-11 ($CFCl_3$) and CFC-12 (CF_2Cl_2) can have the same greenhouse effect as the addition of 10^4 molecules of CO_2 to the present atmosphere (*11*). The important non-CO_2 trace gases that may govern climate change include CFCs, CH_4, N_2O, ozone (O_3), and more than a dozen synthetic chemicals (*12, 13*). These developments set the stage for a number of recent theoretical and model studies (*2, 4, 12, 13*). The conclusions of these studies can be summarized as follows: (i) the observed increases in trace gas concentrations from the mid-19th century to the present have significantly increased the radiative heating of the surface and atmosphere; (ii) there will be a severe reduction of the upper stratosphere O_3 and a cooling of the mid- to upper stratosphere and warming of the surface and troposphere; and (iii) if the observed decadal trace gas growth rate continues unabated, the cumulative surface warming (predicted theoretically) would, in the next two decades, become large enough to manifest itself unambiguously in the global temperature records.

Thus the greenhouse theory of climate change has reached the crucial point of verification because of the inadvertent experiment being performed on the atmosphere by human activities. Revelle and Suess (*14*) coined the phrase "large-scale geophysical experiment" to describe the anthropogenic increase in the atmospheric CO_2 concentration.

Climate Forcing

The greenhouse effect. The important radiatively active gases in the present atmosphere are H_2O, CO_2, and O_3; their ability to intercept IR radiation has been demonstrated by satellite measurements (Fig. 1) (*15*). The upper boundary of the shaded region in Fig. 1 is the emission by the ocean surface (radiating at a temperature of 300 K), whereas the lower boundary is the radiation measured at satellite altitudes; the difference is the net energy absorbed or, alternately, trapped within the lower atmosphere. The absorption features of CO_2 between 13 to 17 μm, O_3 between 9 to 10 μm, and H_2O in the entire spectral domain are seen. On a global-annual average basis, the surface emits about 390 W m^{-2}, whereas the radiation emitted to space, as measured by satellites, is only about 237 W m^{-2}. The balance of 153 W m^{-2} is the IR radiation effectively trapped by the atmosphere (including clouds), which should be compared with the absorbed solar radiation of 237 W m^{-2}. Without this greenhouse effect, the surface would cool to about 255 K (*13*) from its present-day value of 288 K, and the planet would be covered with ice.

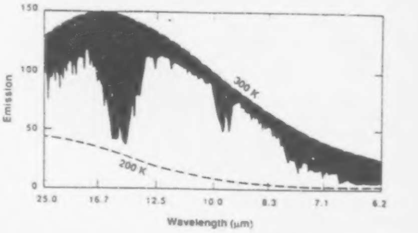


Fig. 1. Sample spectra from the infrared interferometer spectrometer onboard Nimbus 3 satellite. The dashed lines indicate the outgoing long-wave blackbody emission at the temperatures indicated. Emission is measured in arbitrary units. The scene is tropical Pacific Ocean under clear-sky conditions. [Adapted from (*15*) with permission, copyright by American Geophysical Union, Washington, DC]

The human effect: dirtying the atmospheric window. Nearly 80% of the radiation emitted by the surface in the region from 7 to 13 μm escapes to space (Fig. 1) because the atmosphere, at least the preindustrial atmosphere, is quite transparent in this region. Because of the transparency, this region is referred to as the "window." Outside the window region, most of the surface radiation is absorbed by the atmosphere, and then reemitted to space at the much colder atmospheric temperatures (Fig. 1).

Remarkably, most synthetic gases absorb strongly in the window region (Fig. 2), and this absorption by pollutants has literally the effect of "dirtying" the atmospheric window. The synthetic gases are extremely effective compared with CO_2. The radiative energy (ΔQ) trapped in the surface-atmosphere system is estimated to be (*2, 4*): ΔQ(CO_2; from 300 to 600 ppmv) ≈ 4 W m^{-2}; and ΔQ(CFC-11 and CFC-12; from 0 to 2 parts per billion by volume) ≈ 1 W m^{-2}. CFCs are so effective because (i) their absorption occurs in the window region; (ii) their absorption band strengths are significantly stronger than that of CO_2 (Fig. 2); and (iii) the concentration of CO_2 is so large (300 ppm) that this gas is optically thick, and hence its greenhouse effect scales logarithmically with the concentration, whereas the greenhouse effect of CFCs scales almost linearly (*11, 13*).

Climate Response

The response of the climate to an increase in the greenhouse forcing consists of restoring the energy balance at the top of the atmosphere (*8, 13*). I develop the concepts on the basis of a hypothetical zero-dimensional model, which can be expressed as:

$$H\frac{dT'}{dt} = \Delta Q - R' \qquad (1)$$

where H is the heat capacity of the coupled ocean-atmosphere, T' is the surface temperature change, ΔQ is the radiative heating, and R' is the change in the energy leaving the system. If R' is equal to $(dR/dT)T'$ and ΔQ is the heating imposed at time $t = 0$, the equilibrium surface temperature change ΔT_s is the steady-state solution of Eq. 1 given by

$$\Delta T_s = \frac{\Delta Q}{\lambda} \qquad (2)$$

where $\lambda = dR/dT$ is the climate feedback parameter.

The Role of Feedbacks: Water Phase Changes

The parameter λ is determined by the feedback processes in the climate system and has been the subject of research during the last two decades. The current estimate for λ is between 0.9 and 3.6 W m^{-2} K^{-1} (*13*). The upper limit for λ is obtained by assuming that the climate system is devoid of all feedbacks other than IR radiative damping and that it emits IR radiation like a blackbody with an equilibrium temperature of 255 K. Modern day three-dimensional general circulation models (GCMs) yield a value between 0.9 to 1.2 W m^{-2} K^{-1}, yielding a ΔT_s (for doubled CO_2) of 3.5 to 4.5 K (*13, 16, 17*). For a doubling of CO_2, that is, $\Delta Q \approx 4$ W m^{-2}, Eq. 2 and the range for λ given above yield an equilibrium surface warming ΔT_s between 1.1 and 4.5 K. The amplification from the case of a blackbody planet is largely due to feedbacks involving H_2O phase changes.

Liquid to vapor: H_2O greenhouse feedback. This feedback results from the exchange of radiative and latent heat fluxes (Fig. 3) between the atmosphere and the ocean-land surface. Figure 3 illustrates model results for the case of a doubling of CO_2 (*18*). Out of the 4 W m^{-2} of CO_2 heating, roughly 25% is deposited at the surface as increased emission from CO_2, and the balance is trapped in the troposphere. Together, the increase in the IR energy warms the troposphere and the ocean (process 2), which starts the feedback loop 3 in Fig. 3. More moisture evaporates from the warmer ocean and land. The latent heat is released as moisture condenses through precipitation. The warmer troposphere, as a result of the latent heat release and the direct greenhouse heating, holds more vapor for the following reasons: observations of the atmospheric humidity profile as a function of latitude and season suggest that the atmosphere tends to conserve its relative humidity with a change in temperature (*8*); as a result, the absolute humidity is determined by the saturation vapor pressure, which increases exponentially with temperature. The enhanced water vapor, in turn, traps more IR radiation and amplifies the greenhouse effect. In one-dimensional climate models, where this feedback can be selectively turned off, the H_2O greenhouse feedback amplifies the air temperature warming by a factor of ≈1.5 (*17, 18*) and the surface warming by a factor of ≈3 [table 4 in (*18*)].

Solid to liquid and vapor: Ice-albedo feedback. Another well-studied effect is the ice-snow albedo feedback. The greenhouse warming melts the sea ice and snow cover. The underlying surface, be it ocean or land, is much darker than the ice or snow, such that it absorbs more solar radiation, thus amplifying the initial warming. For example, sea ice with overlying snow reflects about 40 to 60% of the solar radiation, whereas the open ocean at high latitudes reflects only 20 to 30%. Melting the sea ice during spring and summer can increase the polar ocean absorption of solar radiation by as much as 50 to 100 W m^{-2}, which should be compared with the direct CO_2 radiative heating of about 4 W m^{-2}. The ice-albedo feedback amplifies the global warming by only 10 to 20% (*17, 19*); but locally, near the sea-ice margins and in polar oceans, the warming can be larger than the global warming by factors ranging from 2 to 4.

Vapor to liquid and solid: Cloud feedback. The increased moisture from the warmer oceans should alter cloud distributions and characteristics. The nature of these cloud changes and how these changes will affect the radiative heating is unclear (*20, 21*). The difficulty is the lack of a theory that can relate cloud scale processes to planetary scale features of clouds. As a result, cloud feedback is one of the largest sources of uncertainty in the theory of climate change. Next to water vapor, clouds play the most dominant role in governing the radiation energy balance of the climate system. For example, the reflectivity of clouds increases the albedo (reflectivity) of the planet from about 10% (the clear sky albedo) to the observed value of 30% (*20*). An increase in the planetary albedo of just 0.5% is sufficient to halve the greenhouse effect of CO_2 doubling. Clouds are also extremely efficient in trapping IR. The tropical cirrus clouds trap as much as 100 to 200 W m^{-2}, and global average values, although not known reliably yet, may be between 25 and 50 W m^{-2} (*20*). Recent GCM studies have indicated that the magnitude of the problem has increased significantly. The GCM sensitivity to CO_2 doubling increased from roughly 2 to 3 K for the models developed in the 1970s to about 4 to 5 K for current models (*16, 17*). One of the major factors that contributed to the increased sensitivity is the inclusion of interactive clouds. However, since clouds are treated primitively in GCMs, it is premature to make reliable inferences from GCM studies.

Ocean-atmosphere interactions. The oceans influence the climate response in two fundamentally important ways. First, because of the importance of the H_2O greenhouse feedback, the response of the tropospheric temperatures and even the land surface temperatures would be governed by the warming of the ocean surface. If for some reason the ocean does not respond to the greenhouse heating, the H_2O feedback would be turned off since increased evaporation from the warmer ocean is the primary source for increasing atmospheric H_2O. Second, oceans can sequester the radiative heating into the deeper layers, which, because of their enormous heat capacity, can significantly delay the warming (*21–23*).

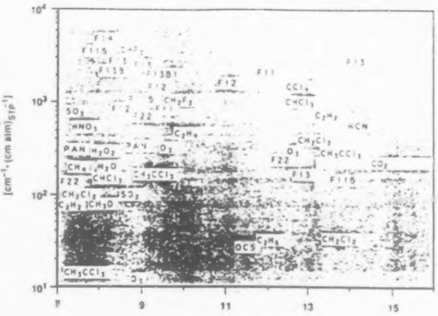


Fig. 2. Spectral locations of the absorption features of various trace gases. The spectral region between 7 and 13 μm is referred to as the atmospheric "window." Abbreviations: F, Freons; PAN, peroxyacetyl nitrate; and STP, standard temperature and pressure. [Adapted from (*13*) with permission, copyright by American Geophysical Union, Washington, DC]

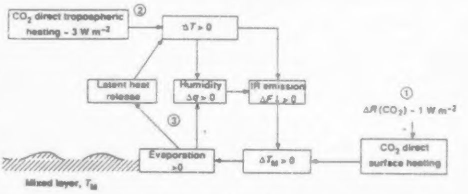


Fig. 3. Schematic of the H_2O feedback involving ocean-atmosphere thermal interactions. This is the dominant mechanism by which the greenhouse feedback warms the surface. Abbreviations: *T*, troposphere temperature; T_M, mixed layer temperature; *F* ↓, downward infrared emission; *q*, specific humidity; and *R*, the radiative (IR plus solar) flux change at the surface due only to change in CO_2. Values correspond to doubling of CO_2. Numbers within circles designate the feedback loops.

Table 2. Estimated increase in the radiative forcing. The value for the global average absorbed solar radiation is 237 W m^{-2}. The uncertainties in the estimates are about ±30%.

Gas	Radiative forcing (W m^{-2})	
	1850–1985 (*4*)	1975–1985 (*13*)
CO_2 only	1.3	0.24
All trace gases	2.2	0.45

Chemical Interactions and Ozone Changes

Stratospheric O_3. There are no known important sinks for CFCs in the troposphere (*24*). They are ultimately broken down in the stratosphere above 25 km by photolysis, which frees the highly reactive chlorine. As a result, their tropospheric lifetimes are long: about 65 years for $CFCl_3$ and 110 years for CF_2Cl_2. The chlorine competes with nitrogen oxides for odd oxygen species including O_3, and the result is an efficient catalytic destruction of O_3 by chlorine until it is removed from the system as HCl. Atmospheric chemistry models predict that, at present rates of emission of CFCs, severe O_3 reduction ranging from 15% near 30 km to about 40% near 45 km (*24*) will result. The stratosphere derives its name because of the increase in temperature with altitude, that is, a stably stratified region. This thermal inversion is maintained by O_3 solar heating, and hence O_3 destruction would cool the stratosphere. For example, a 50% reduction in O_3 would cool the upper stratosphere by as much as 20 K (*13*). Furthermore, O_3 modulates the solar and IR flux incident on the troposphere. A reduction in stratospheric O_3 would allow more sunlight to reach the surface and tend to warm it. This warming will be offset by reduced IR fluxes emitted by the cooler stratosphere and also by a reduced O_3 greenhouse effect. The net effect, that is, surface warming or cooling, critically depends on the vertical distribution of the O_3 change (*8, 13*).

Tropospheric O_3. The 9.6-μm band of O_3 is an important source of IR opacity for the troposphere (*25, 26*). Photolysis of O_3 in the troposphere produces $O(^1D)$, which, in turn, reacts with H_2O to release hydroxyl (OH) radicals through $H_2O + O \rightarrow 2OH$. The highly reactive OH is the primary sink for many tropospheric gases and pollutants including O_3, CH_4, CO, and NO (*25*). Hence, increases in CH_4, such as those during the last century, could have caused a substantial (20 to 40%) reduction in OH (*25*), which in turn, could cause an increase in tropospheric O_3 by as much as 20% (*25, 26*). Since CH_4 oxidation leads to the formation of H_2O, an increase in CH_4, an important greenhouse gas, can lead to an increase in H_2O in the stratosphere. Likewise, an increase in the CO concentration can tie up more OH in the oxidation of CO. Thus, through chemical reactions, an increase in either a radiatively active gas such as CH_4 or even a radiatively inactive gas such as CO can increase the concentrations of several important greenhouse gases (*25*).

Model Predictions

Radiative forcing. The estimated radiative forcing due to the observed trace gas increases is shown in Table 2. Human activities during the last century have enhanced the radiative heating of the planet by an amount (2.2 W m^{-2}) comparable to increasing the sun's output by about 0.9%. During the 1975 to 1985 decade, about 0.45 W m^{-2} was added to the system, and the non-CO_2 gases contributed ≈50% to the total heating.

Equilibrium surface warming. If the planet had no thermal inertia, the trace gas increase would be simultaneously accompanied by the surface warming given by Eq. 2, such that, in Eq. 1, the R' term balances ΔQ at each instant in time. Hence the ΔT_s given by Eq. 2 is referred to as the equilibrium surface warming. For the radiative forcing shown in Table 2, Eq. 2 in conjunction with the range of λ mentioned earlier yields

$$0.6 \leq \Delta T_s(1850 \text{ to } 1985) \leq 2.4 \text{ K} \tag{3}$$

The inferred trace gas increases from the preindustrial era to the present have committed the planet to an equilibrium surface warming of about 0.6 to 2.4 K. Furthermore, at the current rate of increase in the trace gases, the committed equilibrium warming of the globe increases by about 0.13 to 0.5 K per decade. If the current rate of trace gas increase continues unabated, the equilibrium warming can double to 1.2 to 5 K in another 50 years (*4*).

Transient effects. Because of its large thermal inertia, the ocean will sequester some of the radiative heating and hence the transient warming will lag behind the equilibrium warming. Since the trace gases are increasing with time, the lag will increase with time. The important consequence of this transience is that the climate system is increasingly in a state of disequilibrium with the radiative forcing (*17*). The lag, which is currently thought to be in the range of a few decades to a century (*13, 17, 23*), depends on ocean circulation, vertical mixing in the oceans, and the climate feedback parameter (*23*). Data on these three quantities are not adequate. However, the main effect of the ocean in delaying the greenhouse warming can be conceptualized with a simple "box diffusion" model (*22*). This model asserts that heat perturbations are mixed as a passive tracer into the deeper oceans in a manner that can be modeled by one-dimensional diffusion. The vertical penetration of heat anomalies within the oceans, as predicted by the box diffusion models, provides a good fit to the global averaged results of a coupled ocean-atmosphere GCM (*22*). The values of the diffusion coefficient, k, that yield good agreement with measurements of passive tracers are between 1 to 2 $cm^2 sec^{-1}$. Analytical studies of these conceptual models suggest (*23*) that for a heating pulse switched on abruptly, the lag behaves as k/λ^n where $1 \leq n \leq 2$ (*23*). For the realistic case of a heating perturbation that is growing with time, the concept of a thermal lag is not very useful. A more useful parameter is β, which is the ratio of the transient temperature change to the equilibrium warming. For the observed trace gas changes of the past century, β varies from ≈0.45 for $\lambda = 0.9$ W $m^{-2} K^{-1}$ to ≈0.75 for $\lambda = 3.6$ W $m^{-2} K^{-1}$ (*13, 23*). If we apply these values of β to Eq. 3, the expected trace gas warming from 1850 to 1985 is estimated to be between 0.5 and 1.1 K. Because of the inverse relation between the lag and λ, the fourfold range in the equilibrium warming has severely been reduced in the transient case.

Other changes. The following effects are largely derived from GCM studies of the CO_2 doubling problem (*2*): (i) the warmer globe will be more humid and wetter; and (ii) the warming will be amplified in the polar regions by factors of 1.5 to 3 (*2, 16, 17*). The threefold amplification occurs mainly during the winter season over the margins of sea ice between 50° and 70° latitude. The warming in the high-latitude continents peaks during spring and is larger by roughly a factor of 1.5 than the global average warming (*16, 17*). Other postulated effects include summer drying in mid-latitudes and a rise in sea level (*2*). The degree of uncertainty in the computed regional changes is significantly larger than the global average estimates (*2*).

Stratospheric cooling. The computed surface warming is accompanied by a significant cooling of the mid- to upper stratosphere, that is, at altitudes above 30 km (*4, 13, 14*). The cooling is partly due to increased IR emission from the CO_2-rich stratosphere and due to the reduced solar heating from the O_3 reduction that is predicted to

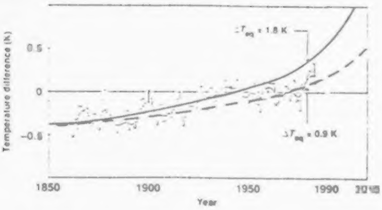


Fig. 4. Comparison of observed (*28*) and computed (*13*) global annual-averaged surface temperature anomalies. The computed anomalies are based on calculations of Lacis and Hansen [as reported in (*13*)] who used a one-dimensional box-diffusion ocean-atmosphere model. The equation for the solid line is λ (see Eq. 2) = 1 W m^{-2} K^{-1}; *k* (diffusion coefficient) = 1 cm^2 sec^{-1}; current growth rates for trace gas increase beyond 1985; the equilibrium warming for 1850 to 2030 is 5.4 K. The equation for the dotted line is λ = 2 W m^{-2} K^{-1}; *k* = 2 cm^2 sec^{-1}; reduced growth rates [details in (*13*)]; the 1850 to 2030 equilibrium warming is 2 K. [Adapted from (*13*) with permission, copyright by American Geophysical Union, Washington, DC]

result from the CFC increase. For the period 1860 to 1985, the combined computed effect of CO_2 increase and the CFC increase is as follows: −1 K at 25 km; −2.5 K at 30 km; and a maximum cooling of about 6 K between 45 to 50 km.

The Evidence for Change

The control climate. A control climate needs to be established against which the changing climate can be compared. For example, the climate of the last 12,000 years is significantly different from that of the previous 12,000 years when there was the Great Ice Age; the climate of the last 200 years was different from that of the previous 200 years, which were subject to the Little Ice Age; and the climate of the last 50 years was also much warmer than that of the previous 50 years, when Alpine glaciers were at their southernmost extent. Against such a background of changing climate, the definition of a control climate is not clear, as pointed out by Lorenz (*27*).

Whether the past changes are simply the result of aperiodic behavior of a nonlinear system (*27*) or the result of changes in the climate forcing terms has not been settled yet. However, it should be remembered that summer is always warmer than winter in most latitudes and the tropical regions are always warmer than the poles. These seasonal and latitudinal climate changes are related to the solar forcing. Thus, the following question is raised: Is the human effect large enough to overwhelm the background changes, whatever these may be?

Surface warming. Widespread instrumental records of hemispherical scale surface temperature were begun only in the 1850s; therefore, calibrated records of the climate system before this time do not exist. The spatial sampling is poor before 1900, hence there is a considerable discrepancy in even the sign of the changes between the 1850s and 1900 (*28, 29*). Until a few years ago, the estimates of the global average temperature were largely based on records from land and island stations. The compilation of ocean temperature measurements made on ships was undertaken only recently. A reconstruction of global average temperature (*28*), which includes land and marine temperatures, along with computed temperatures is given in Fig. 4. The observed records reveal a global warming of about 0.5 K from 1850 to 1985; however, the temporal history of the warming and the trace gas increases have varied. For example, the global warming that began in the early 20th century was interrupted during the period 1940 to 1970, when there was a substantial increase in the trace gas forcing.

The observed variations can be described with phase diagrams of just the hemispherical station-averaged temperatures (Fig. 5). The variations are smoothed first by taking time averages of 3 or 5 years (*30*). One 3- or 5-year average (*x*-axis) is plotted against the following 3- or 5-year average (*y*-axis). In such a diagram, a linear trend will show as a diagonal line; periodic variation as a circle or closed loop; and aperiodic variations will be intersecting contours. For both hemispheres, the late-19th-century points fall in the southwest quadrant, whereas the late-20th-century points fall in the northeast quadrant, which confirms the existence of an overall warming trend (*28, 31*). However, most of the warming in the Northern Hemisphere takes place abruptly over a 10- to 15-year period (seen in the 5-year average in Fig. 5B), whereas it takes place in a series of "staircase" patterns in the Southern Hemisphere, that is, a warming in one 3- to 5-year period followed by another period of almost no change. Similarly, the substantial warming in the 1970s and early 1980s happened mostly in one 3- to 5-year period in both the hemispheres. The abrupt nature of the climate change, recognized also by earlier studies (*29*), may be a feature of climate changes on the 1,000- to 10,000-year time scales (*32*).

Polar amplification. Observed trends have generally revealed that the global temperature changes are accompanied by significantly larger changes in the polar regions (*20, 31*). This result, by itself, does not verify trace gas effects but does add credence to the polar amplification theory.

Stratospheric cooling. Two studies (*33, 34*) dealing with radiosonde data have shown that the lower stratosphere has cooled since 1965 when global coverage by radiosondes began. Angell's analyses (*33*) show the following global trends for the period 1965 to 1980: −0.14 K per decade for 16 to 20 km and −0.33 K per decade for 16 to 24 km, whereas Labitzke *et al.* (*34*) found −0.24 K per decade at 30 mbar (≈24 km). These decreases should be compared with the computed trace gas cooling trend of about 0.3 K per decade at 30 mbar (*34*). However, it is premature to consider this agreement in trends as verification because of the limited duration of the data.

Other Competing Forcings

Various other radiative forcing terms can influence decadal scale climate changes (*17, 21*); two of them are described here.

Solar irradiance. Accurate measurements of the solar irradiance reveal that the solar irradiance has decreased by 0.1% between 1979 to 1984, which translates into a decrease in the radiative heating of about 0.25 W m^{-2} (*35*). These measurements support the suggestions (*36*) that link climate changes to variations in solar irradiance.

Volcanoes. After the eruption of Laki in Iceland in 1783, Benjamin Franklin suggested that volcanic aerosol clouds in the upper atmosphere scatter sunlight and reduce the solar radiation reaching the surface. Since then, there has been speculation about the surface cooling due to volcanoes. Modern-day measurements have helped resolve some of the controversy surrounding the hypothesis. For example, it is known that volcanoes can eject aerosol precursor gases into the stratosphere; these gases spread globally over a period of several months and are converted to sulfuric acid droplets in the stratosphere (*37*).

The sulfuric acid droplets absorb the longwave radiation emitted by the warmer surface and cause a local heating of the stratosphere. The heating is particularly large within the tropical lower stratosphere because of the warm tropical surface, which enhances the IR radiation intensity, and the very cold lower stratosphere, which minimizes emission of IR radiation by the aerosols. The temperature warming due to this heating will reach a maximum in the lower stratosphere because of its long radiative response time (50 to 100 days). Thus, a heating of only 0.05 K day^{-1} will cause a warming of 3 to 5 K in the lower stratosphere, as was observed in the tropics after the El Chichón eruption in April 1982 (*38*). This confirmation is perhaps the only aspect of the entire climate theory for which there is unambiguous verification.

After the El Chichón eruption in April 1982, the stratospheric visible optical depth in tropical to mid-latitude regions maintained peak seasonally averaged values of about 0.1 to 0.2 for nearly 6 months (*37*) and took about 2 to 3 years to decay to the background values that are less than 0.005. A stratospheric cloud with an optical depth of 0.1 can reflect back to space as much as 3.5 W m^{-2} (*39*). A major eruption, such as El Chichón, with an initial optical depth of 0.1 decaying in 3 years, could contribute as much as 0.2 to 0.4 W m^{-2} to decadal average radiative cooling, which should be compared with the 0.45 W m^{-2} trace gas heating for 1975 to 1985 (Table 2). Although the radiative effects of volcanic aerosols are understood, the surface cooling effect of volcanoes has not yet been satisfactorily demonstrated (*40, 41*).

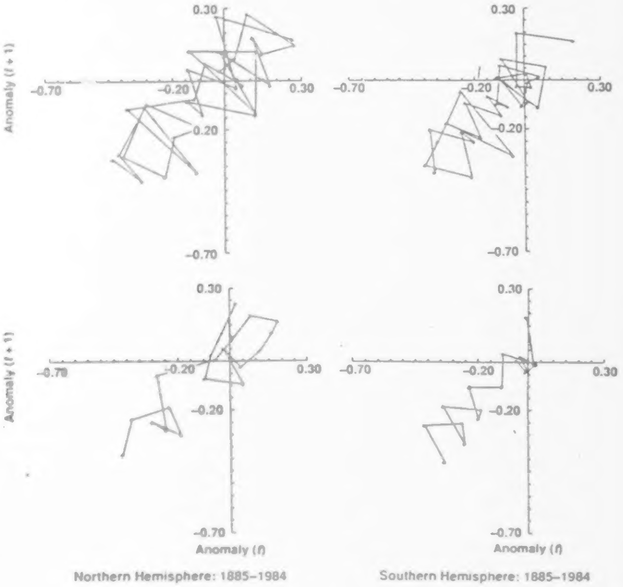
Summary and Discussion

The fundamental effect of the time-dependent trace gas radiative heating is to push the climate system into a state of disequilibrium with the incoming and outgoing energy fluxes. The theory states that the earth tries to restore the equilibrium by warming and by emitting the excess energy to space; about 0.5 to 1 K of this warming should have already occurred. Observed records do reveal a warming of the order of about 0.5 K, but the temporal history of the warming is unlike the pattern anticipated by the theory. The warming occurred abruptly and in bursts. Either the observed warming is not related to the increase in the trace gases or current theories and models of ocean-atmosphere interactions are inadequate to capture the transient response of the climate system to a time-dependent variation in external forcing. The theoretical understanding of the climate system is by no means complete. Some issues that need to be resolved follow.

Climate extremes. If the trace gases continue to increase, the warming, according to the sensitivity of GCMs, can reach 5 K during the next century. A warming of this magnitude would be unprecedented because the present climate is just coming out of the peak of an interglacial period. A warming of 5 K above this peak would likely be beyond the range of validity of current models, particularly with respect to the response of the world's ice sheets and changes in the ocean circulation. On the other extreme, the Vostok ice store (Antarctica) data (*6*) reveal that CO_2 has decreased from about 280 ppm during interglacial to about 190 ppm during glacial time. Furthermore, it has been suggested that the CO_2 variations themselves may help explain the glacial-interglacial cycles (*6*). The radiative cooling due to a CO_2 decrease from 280 to 190 ppm is only 2.5 W m^{-2}; for this cooling to institute a major ice age requires a climate sensitivity even larger than those of current GCMs (*6*).

Cloud microphysics. Recent studies (*42–45*) have made compelling arguments to link cloud microphysics with climate change. The cloud visible optical depth, τ, can be written as $\tau = CL/r$, where C is a constant, L is the cloud liquid water content, and r is the droplet radius. The above relation follows from the fact that r is large enough (≈ 10 μm) that the scattering can be approximated by geometrical optics, that is, independent of wavelength or radius. The liquid water content $L = (4/3)\pi r^3 N$, where N, the number of cloud droplets, is closely correlated with condensation nuclei. Hence, on combining the above relation for L and τ, one has

$$\tau = cL^{2/3}N^{1/3} \tag{4}$$



Northern Hemisphere: 1885–1984

Southern Hemisphere: 1885–1984

Fig. 5. Phase-plane diagram of observed surface air temperature anomalies. The data are deviations of the hemispherical mean temperatures from the 1959 to 1984 average. Only land stations are included in the hemispherical average. The figure plots 3-year (**top**) and 5-year (**bottom**) averages (*x*-axis) against the following 3- and 5-year averages (*y*-axis). The starting period is on the lower southwest quadrant of each diagram, since the early 19th century was a cold period. The initial year is 1885, since the data have severe sampling problems before this period.

where c is a constant. The increase in absolute humidity with T_s could lead to an increase in L (*42*). The resulting increase in τ (Eq. 4) will enhance cloud reflection of solar radiation and provide a negative feedback (*42*). Another mechanism of negative feedback (*43*) suggests that human activities have also increased tropospheric particulates, and this will lead to an increase in N. A variant of this feedback, which involves biogenic processes, has been proposed by Charlson *et al.* (*44*). They pointed out that the value of N over the oceans is predominantly sulfuric acid droplets derived from emission of dimethyl sulfide by marine organisms. They suggested that an increase in T_s may cause an increase in emission of dimethyl sulfide and hence N. These suggestions received indirect support from a recent satellite study (*45*), in which ship tracks that had been spotted amidst marine stratocumulus clouds were consistently brighter in visible wavelengths. This brightness was not due to particulates from the ship smoke (these would be darker) but was due to enhanced cloud condensation nuclei, from the sulfur in the smoke, which enhances cloud visible optical depth according to Eq. 4.

Influence of CH_4, H_2O, and stratospheric clouds. The increase in CH_4 of nearly a factor of 2, along with the various ways it can influence the atmosphere, makes it one of the most intriguing greenhouse gases. An increase in CH_4, because of its coupling with OH, can cause an increase in tropospheric O_3. Also, CH_4, which is oxidized to H_2O in the atmosphere, is an important source for stratospheric H_2O (*13, 17*). In principle, CH_4 can be oxidized to two H_2O molecules. The observed increase in CH_4 from 0.7 to 1.7 ppmv (*4*) can lead to a maximum increase in H_2O of 2 ppmv. The observed H_2O concentration in the stratosphere increases from about 2 to 5 ppmv near the tropical tropopause (10 to 16 km) to about 5 to 8 ppmv above 30 km (*46*). Most of this increase could be due to an increase in CH_4 from the preindustrial to the present time. Stratospheric H_2O enhances the greenhouse effect substantially; a doubling of stratospheric H_2O (entire column) from 5 ppmv can have nearly the same warming effect (*8, 12*) as that due to the observed CO_2 increase during the last century. Because H_2O and other gases are also transported poleward and downward in the stratosphere (*47*), H_2O produced in the tropical middle and upper stratosphere by CH_4 oxidation can be transported to the polar lower stratosphere. This H_2O may contribute to the recently discovered polar stratospheric clouds (*37*) in two ways. First, H_2O may provide the required source for the liquid and solid H_2O in the clouds (*48*). Second, the local radiative cooling from the increased H_2O (*49*) may provide the temperature drop needed for cloud formation. Since the radiative response time of the lower stratosphere is of the order of 50 to 100 days, an increase in the cooling rate of 0.02 to 0.05 K day^{-1} may cool the region by 2 to 3 K (*49*). This cooling is sufficient for H_2O, even at 5 ppmv, to condense in the Antarctic lower stratosphere during winter. Thus climate effects of CH_4 may involve complex interactions among atmospheric chemistry, radiation, thermodynamics, and dynamics.

REFERENCES AND NOTES

1. J. B. Fourier, *Mem. Acad. Sci. Inst. Fr.* 7, 569 (1827).
2. B. Bolin, B. R. Döös, J. Jager, R. A. Warrick, Eds., *The Greenhouse Effect, Climatic Change and Ecosystems* (Wiley, New York, 1986). This book resulted from an international conference organized by the International Council of Scientific Unions at Villach, Austria, in October 1985.
3. R. A. Rasmussen and M. A. K. Khalil, *Science* 232, 1623 (1986).
4. R. E. Dickinson and R. J. Cicerone, *Nature (London)* 319, 109 (1986).
5. S. Arrhenius, *Philos. Mag.* 41, 237 (1896).
6. J. Jouzel *et al.*, *Nature (London)* 329, 403 (1987); J. M. Barnola, D. Raynaud, Y. S. Korotkevich, C. Lorius, *ibid.*, p. 408; G. Genthon *et al.*, *ibid.*, p. 414.
7. G. S. Callendar, *Q. J. R. Meteorol. Soc.* 64, 223 (1938).
8. S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* 24, 241 (1967).
9. Manabe and Wetherald (*8*) suggested that the surface and the troposphere are so strongly coupled by convective, that is, vertical, heat transfer processes that the surface temperature is governed not only by the radiative heating at the ground but by the heating of the joint surface-troposphere system. Furthermore, this development made the stratosphere and stratospheric O_3 an integral part of the climate system. For example, a reduction in stratospheric O_3 would reduce the solar heating, which in turn would cool the stratosphere. The stratosphere would then emit less IR to the troposphere. Because of convective coupling of the entire troposphere with the surface, the reduction in downward IR emission from the stratosphere can cause a surface cooling.
10. J. T. Kiehl and R. E. Dickinson, *J. Geophys. Res.* 92, 2991 (1986); E. J. Barron and W. M. Washington, *ibid.* 90, 1267 (1984).
11. V. Ramanathan, *Science* 190, 50 (1975).
12. W. C. Wang, Y. L. Yung, A. A. Lacis, T. Mo, J. E. Hansen, *ibid.* 194, 685 (1976); V. Ramanathan, *Energy/Climate Interactions* (Reidel, Dordrecht, 1980), pp. 269–280; A. Lacis *et al.*, *Geophys. Res. Lett.* 8, 1035 (1981); W. C. Wang *et al.*, *Rev. Geophys.* 24, 110 (1986); C. Tricot and A. Berger, *Climate Dyn.* 2, 39 (1987); C. Brühl and P. J. Crutzen, *ibid.* 2 (3), 173 (1988).
13. V. Ramanathan *et al.*, *Rev. Geophys.* 25, 1441 (1987).
14. R. Revelle and H. E. Suess, *Tellus* 9, 18 (1957).
15. R. A. Hanel *et al.*, *J. Geophys. Res.* 77, 2629 (1972).
16. The recent GCM studies with the higher sensitivity include: C. A. Wilson and J. F. B. Mitchell, *J. Geophys. Res.* 92, 13315 (1987); W. M. Washington and G. A. Meehl, *ibid.* 89, 9475 (1984); R. T. Wetherald and S. Manabe, *Clim. Change* 8, 5 (1986); M. E. Schlesinger and J. F. B. Mitchell, *Rev. Geophys.* 25, 760 (1987).
17. J. Hansen *et al.*, in *Climate Processes and Climate Sensitivity*, J. E. Hansen and T. Takahashi, Eds. (American Geophysical Union, Washington, DC, 1984), vol. 5, pp. 130–163.
18. V. Ramanathan, *J. Atmos. Sci.* 38, 918 (1981).
19. M. S. Lian and R. D. Cess, *ibid.* 34, 1058 (1977).
20. R. D. Cess, *ibid.* 33, 1831 (1976).
21. National Research Council, *Carbon Dioxide and Climate: A Second Assessment* (National Academy Press, Washington, DC, 1982).
22. K. Bryan *et al.*, in *Climate Process and Climate Sensitivity*, J. E. Hansen and T. Takahashi, Eds. (American Geophysical Union, Washington, DC, 1984), vol. 5, pp. 29–38.
23. T. M. L. Wigley and M. E. Schlesinger, *Nature (London)* 315, 649 (1985).
24. R. J. Cicerone, *Science* 237, 35 (1987).
25. A. M. Thompson and R. J. Cicerone, *J. Geophys. Res.* 91, 10,853 (1986); S. Hameed *et al.*, *ibid.* 85, 7537 (1980).
26. J. Fishman, V. Ramanathan, P. J. Crutzen, S. C. Liu, *Nature (London)* 282, 818 (1979).
27. E. N. Lorenz, *Tellus* 16, 1 (1964).
28. P. D. Jones, T. M. L. Wigley, P. B. Wright, *Nature (London)* 322, 430 (1986); A. H. Oort *et al.*, *Climate Dyn.* 2, 29 (1987).
29. H. W. Ellsaesser *et al.*, *Rev. Geophys.* 24, 745 (1986).
30. The temperature data were obtained from P. D. Jones *et al.* [*Tech. Rep. 22* (Carbon Dioxide Division, Department of Energy, Washington, DC, 1986)] and processed by K. Sembach, University of Chicago.
31. The analyses of the data in (*30*) reveal a warming trend of about 0.4 to 0.5 K in both hemispheres for 1885 to 1984. There is a factor of 2 to 3 poleward amplification of the trend; furthermore, the magnitude peaks during winter.
32. W. S. Broecker [*Nature (London)* 328, 123 (1987)] used deep-sea sediment records to suggest that the transition from glacial to the interglacial occurred abruptly about 15,000 years ago and that since then there were two relapses into cold climates of several centuries duration with a rapid recovery to the warm climate.
33. J. K. Angell, *Mon. Weather Rev.* 114, 1922 (1986).
34. K. Labitzke *et al.*, *Geophys. Res. Lett.* 13, 52 (1986).
35. R. C. Willson, H. S. Hudson, C. Frohlich, R. W. Brusa, *Science* 234, 1114 (1986).
36. G. C. Reid, *Nature (London)* 329, 142 (1987).
37. M. P. McCormick and C. R. Trepte, *J. Geophys. Res.* 92, 4297 (1987).
38. K. Labitzke *et al.*, *Geophys. Res. Lett.* 10, 24 (1982).
39. A. Harshvardan, *J. Atmos. Sci.* 36, 1274 (1979); M. D. King *et al.*, *J. Climate Appl. Meteorol.* 23, 1121 (1984).
40. P. M. Kelly and C. B. Sear, *Nature (London)* 311, 740 (1984); C. Mass and S. H. Schneider, *J. Atmos. Sci.* 34, 1995 (1977).
41. S. Self *et al.*, *J. Volcanol. Geotherm. Res.* 11, 41 (1981); M. R. Rampino, S. Self, R. W. Fairbridge, *Science* 206, 826 (1979).
42. R. C. J. Somerville *et al.*, *J. Geophys. Res.* 89, 9668 (1984).
43. H. B. Twomey *et al.*, *Tellus* 36B, 356 (1984).
44. R. J. Charlson, J. E. Lovelock, M. O. Andreae, S. O. Warren, *Nature (London)* 326, 655 (1987).
45. J. A. Coakley, Jr., R. L. Bernstein, P. A. Durkee, *Science* 237, 1020 (1987).
46. H. W. Ellsaesser *et al.*, *Planet. Space Sci.* 28, 827 (1980).
47. J. D. Mahlman *et al.*, *J. Geophys. Res.* 91, 2687 (1986).
48. V. Ramanathan, paper presented at the Dahlem Workshop, Berlin, 1 to 6 November 1987; D. R. Blake and F. S. Rowland, *Science* 239, 1129 (1988).
49. The potential radiative cooling effect of H_2O vapor in the polar lower stratosphere is discussed by V. Ramanathan *et al.* [*J. Atmos. Sci.* 40, 605 (1983)]. They suggest (p. 623) that a doubling of lower polar stratosphere H_2O can enhance the radiative cooling by 0.05 to 0.1 K day^{-1}. The radiative response time of 50 to 100 days for the lower stratosphere is cited in the above reference, but earlier studies have also pointed this out, for example, S. B. Fels *et al.*, *J. Atmos. Sci.* 37, 1077 (1980). Because of this slow response time, excess H_2O brought down to the lower stratosphere during the fall season can result in a temperature drop during winter.
50. Supported by NSF grant ATM8700286 and NASA grant NAS1-18385. I gratefully acknowledge comments by J. Mahlman and J. Perry. I thank J. Mills for the French translation, K. Sembach for the data analyses, and the Department of Energy, Washington, DC, for supplying the data in (*30*).

Research Articles

Cloud-Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment

V. RAMANATHAN, R. D. CESS, E. F. HARRISON, P. MINNIS, B. R. BARKSTROM, E. AHMAD, D. HARTMANN

The study of climate and climate change is hindered by a lack of information on the effect of clouds on the radiation balance of the earth, referred to as the cloud-radiative forcing. Quantitative estimates of the global distributions of cloud-radiative forcing have been obtained from the spaceborne Earth Radiation Budget Experiment (ERBE) launched in 1984. For the April 1985 period, the global shortwave cloud forcing [−44.5 watts per square meter (W/m^2)] due to the enhancement of planetary albedo, exceeded in magnitude the longwave cloud forcing (31.3 W/m^2) resulting from the greenhouse effect of clouds. Thus, clouds had a net cooling effect on the earth. This cooling effect is large over the mid- and high-latitude oceans, with values reaching −100 W/m^2. The monthly averaged longwave cloud forcing reached maximum values of 50 to 100 W/m^2 over the convectively disturbed regions of the tropics. However, this heating effect is nearly canceled by a correspondingly large negative shortwave cloud forcing, which indicates the delicately balanced state of the tropics. The size of the observed net cloud forcing is about four times as large as the expected value of radiative forcing from a doubling of CO_2. The shortwave and longwave components of cloud forcing are about ten times as large as those for a CO_2 doubling. Hence, small changes in the cloud-radiative forcing fields can play a significant role as a climate feedback mechanism. For example, during past glaciations a migration toward the equator of the field of strong, negative cloud-radiative forcing, in response to a similar migration of cooler waters, could have significantly amplified oceanic cooling and continental glaciation.

CLOUDS ARE REGULATORS OF THE RADIATIVE HEATING OF the planet. They reflect a large part of the incoming solar radiation, causing the albedo of the entire earth to be about twice what it would be in the absence of clouds (*1*). Clouds also absorb the longwave (LW) radiation (also known as infrared or thermal radiation) emitted by the warmer earth and emit energy to space at the colder temperatures of the cloud tops. Cloud LW absorption and emission are, in a sense, similar to the radiative effects of atmospheric gases. The combined effect of LW absorption and emission—that is, the greenhouse effect—is a reduction in the LW radiation emitted to space. The greenhouse effect of clouds may be larger than that resulting from a hundredfold increase in the CO_2 concentration of the atmosphere (*2*).

How these two competing effects of clouds vary with time, geography, or cloud type and structure is not well understood; nor do we know how clouds modulate meridional and regional radiative heating. Such heating drives the general circulation of the atmosphere and oceans. Significantly different estimates of cloud radiative effects have been used in models of past and future climates. In short, the fundamental question, whether clouds cool or warm the climate, has remained unanswered.

Cloud-radiative interactions represent a large source of uncertainty in several areas including: (i) the prediction of climate changes associated with an anthropogenic increase in trace gases, and (ii) the understanding of past and future climate changes caused by variations in the solar constant or the orbital parameters of the earth (*3*, *4*). General circulation model (GCM) studies (*4*) have contributed to our understanding of cloud-climate feedback, and limited observational studies (*5*) have aided the identification of complex mechanisms of cloud-climate interaction. However, a global perspective on cloud-radiative interactions based on observations has been lacking.

Observations of the modulation of the solar and LW radiation fluxes by clouds can provide needed insights into the cloud-climate interaction. Such modulations are called the shortwave (SW) and longwave cloud-radiative forcing (*6*). We have obtained quantitative estimates of the global distributions of SW and LW forcing from the Earth Radiation Budget Experiment (ERBE), a system of satellites that provides data on incoming and emitted radiation (*7*). In this article, we develop the cloud-radiative forcing concept, describe global variations in the forcing on the basis of the ERBE data, and, finally, discuss the implications of these data for understanding past and future climatic changes.

Description of ERBE. The ERBE includes three satellites in different orbits, a system that improves temporal sampling and can provide data on diurnal variations. The Space Shuttle Challenger launched the first of three satellites, the Earth Radiation Budget Satellite (ERBS), in October 1984. The second satellite (National Oceans and Atmospheric Agency, NOAA-9) was launched in December 1984. The third (NOAA-10) was launched in July 1986 (*8*). In our study, we used data gathered by the ERBS and NOAA-9 satellites. Each satellite contained a pair of instrument packages: a scanner and a nonscanner; we used the scanner measurements only. The scanner footprint at nadir, that is, looking down, was about 35

V. Ramanathan is a professor in the Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637. R. D. Cess is a professor at the Institute for Atmospheric Sciences, State University of New York at Stony Brook, Stony Brook, NY 11794. E. F. Harrison, P. Minnis, and B. R. Barkstrom are with the Atmospheric Sciences Division, NASA Langley Research Center, Hampton, VA 23665. E. Ahmad is in the Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637. D. Hartmann is a professor in the Department of Atmospheric Sciences, University of Washington, Seattle, WA 98195.

km. During flight, observations of internal black bodies and the sun were used to calibrate the measurements. Independently monitored tungsten lamps also provided a relative check of the SW calibration. A solar monitor on the nonscanner instrument measures solar irradiance. We use this measurement to calculate the geographic distribution of incident sunlight. The instruments on the scanner measure the reflected SW and the emitted LW fluxes at the top of the atmosphere. The difference between the incident flux and the reflected SW flux gives the solar energy absorbed by the surface-atmosphere column. The emitted LW flux is the energy radiated away by the column. The difference between the absorbed and emitted flux is the net radiative heating of the surface-atmosphere column. We combined the radiation budget data from ERBS and NOAA-9 satellites to produce diurnal average fluxes on a daily basis. Then, we averaged these daily fluxes over the days in the month to produce the data presented. We discuss below the completed analyses for April 1985. Our initial analyses of data available for other months support the conclusions based on the April 1985 data.

The cloud-radiative forcing concept. Let us consider a domain of an area large enough to contain regions of overcast skies and regions of clear skies. In the overcast regions, water vapor occurs with condensed water or ice, or both; in the clear sky regions, water occurs only in the vapor phase. The domain can be the whole earth, an entire latitude belt, or a specific region on the globe. Typically, such a domain would be a composite of overcast and clear skies and is referred to, usually, by meteorologists as cloudy. The term cloudy should not be confused with the term overcast. A cloudy domain is overcast only when it is completely covered with clouds.

The net radiative heating, H, for the entire surface-to-atmosphere column of a cloudy domain is

$$H = S(1 - \alpha) - F \tag{1}$$

where S is the solar irradiance and α is the albedo; hence $S(1 - \alpha)$ is the absorbed solar radiation. F is the LW flux emitted to space.

To describe the effects of clouds on H from observations, we first define the cloud forcing C

$$C = H - H_{clr} \tag{2}$$

where H_{clr} is the clear-sky net heating. If a domain has no clouds, $H = H_{clr}$ and $C = 0$. Thus, clouds should cause any difference between the net radiative heating averaged over the domain and the

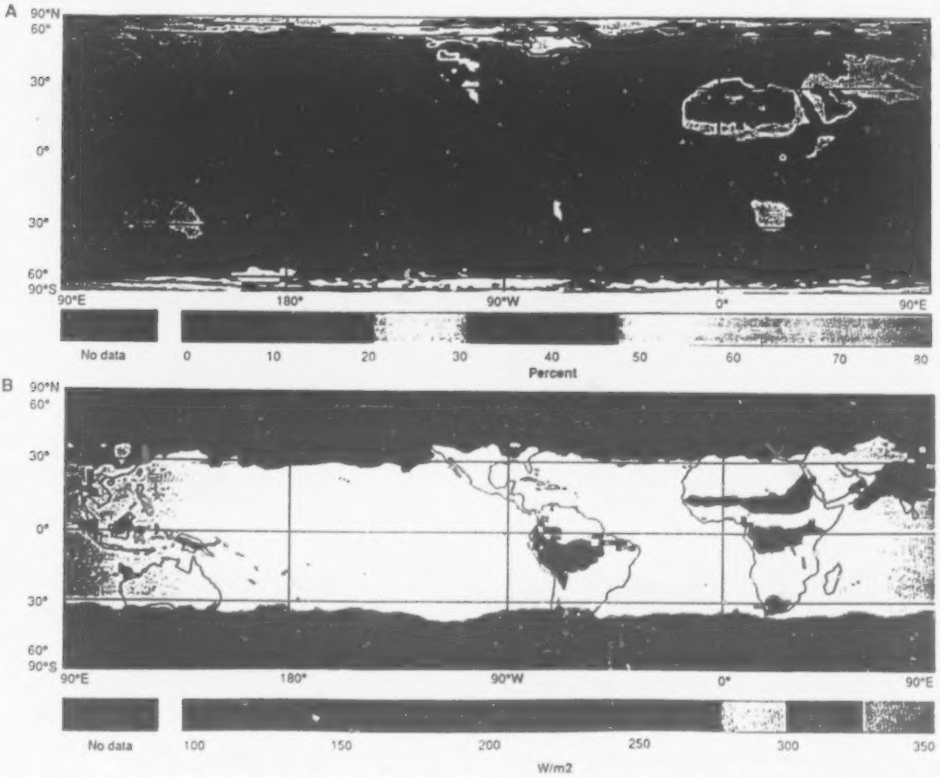


Fig. 1. (**A**) Clear-sky albedo, monthly averages for April 1985. Data from the scanners on-board ERBS and NOAA-9 satellites have been combined. (**B**) same as (A), but for clear-sky LW flux.

heating averaged only over the clear-sky regions in that domain. From Eqs. 1 and 2, we can write C as

$$C = C_{SW} + C_{LW} \tag{3}$$

where $C_{SW} = S(\alpha_{clr} - \alpha)$ and $C_{LW} = F_{clr} - F$; α_{clr} is the clear-sky albedo and F_{clr} is the clear-sky LW radiation flux.

Clouds are almost always more reflective than the ocean surface and land, except where there is snow. Thus, when clouds are present, they reflect more solar energy into space than would clear skies. The SW cloud forcing, C_{SW}, gives a quantitative estimate of this effect. C_{SW} is simply the difference between the clear-sky and cloudy-sky reflected solar fluxes. When clouds are present, the atmospheric column radiates less thermal energy into space than it would if the skies were clear. The LW cloud forcing (C_{LW}) measures this effect. The net effect of clouds is simply the sum of the LW and SW cloud forcing (Eq. 3). Equations 1 to 3 can also be derived in a slightly different way (8), which leads to a cloud forcing expression in cloud fraction and radiative fluxes from overcast skies. For example, $C_{SW} = S(\alpha_{clr} - \alpha)$ is equal to

$$S(\alpha_{clr} - \alpha) = S \sum_i f_i (\alpha_{clr,i} - \alpha_{o,i}) \tag{4}$$

In Eq. 4, the domain is subdivided into i subregions, f_i is the cloud fraction and $\alpha_{o,i}$ is the overcast albedo for region i.

Obtaining the forcing from the expression on the left-hand side of Eq. 4 is simpler and more effective than obtaining it from the right-hand side. First, the clear-sky fluxes are significantly more homogeneous than overcast sky fluxes. As a result, the extension of clear-sky fluxes to the entire domain minimizes the errors caused by poor spatial and temporal sampling. Second, estimation of poorly constrained quantities, such as cloud fractions, is not necessary. Thus, obtaining the cloud-radiative forcing reduces to the relatively simple (but still difficult) problem of measuring the clear-sky fluxes (9).

The spatial resolution of meteorological scanners is not small enough to allow identification of all the clear-sky areas in a region, but this is not a problem because we do not anticipate systematic variations in the clear-sky fluxes as a function of resolution. Clear scenes that are larger than the resolution of the telescope should have the same fluxes as smaller clear scenes. Observations for periods longer than a week should average variations caused by random scene-to-scene differences. Another potential problem occurs where an entire region is overcast. In such regions, we can still infer a cloud forcing by enlarging the size of the region so that it includes some clear skies. An equivalent procedure is the adoption of an average of the clear-sky fluxes estimated for the surrounding regions. The uncertainty in the estimates increases with the spatial inhomogeneity of regional-scale clear-sky fluxes. Our results show that the clear-sky fluxes among adjacent regions are significantly more homogeneous than the fluxes for average cloudy conditions.

ERBE observations of clear-sky albedo and LW flux. The distribution of clear-sky albedo (Fig. 1A) reveals that the oceans are the darkest regions of the globe. They have albedos that range from 6 to 10 percent in the low latitudes to 15 to 20 percent near the poles. Ocean albedo increases toward high latitudes because the albedo of the surface increases as the sun lowers in the sky (10). The brightest parts of the globe are the snow-covered Arctic and Antarctic. Next in brightness to the snow-covered regions are the major deserts. The Saharan and Saudi Arabian deserts reflect as much as 40 percent of the incident solar radiation. The other major deserts, the Gobi and Gibson deserts, reflect about 25 to 35 percent. The tropical rain forests in South America and Central Africa have albedos from 10 to 15 percent. They are the darkest land surfaces on the earth.

The clear-sky LW radiation data (Fig. 1B) show a more systematic pattern. Emission decreases from a maximum of 330 W/m^2 in the tropics to about 150 W/m^2 in the polar regions. Although the clear-sky observations contain no major surprises, they do provide quantitative estimates of the distribution of clear-sky radiative heating.

Statistics of clear-sky fluxes and uncertainties. The accuracy of the estimates for regional and time-averaged clear-sky fluxes depends on the homogeneity of the clear region fluxes. The spatial resolution of the scanner is not sufficient to detect all of the clear regions in the domain of interest. The error attributed to this poor sampling depends on the spatial and temporal variability of the clear-sky fluxes. To demonstrate that the clear-sky flux estimates were accurate, we computed their standard deviation (σ) for several spatial

Table 1. Standard deviation of clear-sky LW and SW fluxes (in parentheses) in watts per meter squared. Four overlapping scans were used to estimate the pixel scale σ's. Each scan contains 62 pixels. All of the clear-sky pixels in the four-scan set entered the computation of a mean and a standard deviation. The pixels were also sorted into 2.5° by 2.5° regions. The clear-sky data for 1 day then yield regional σ values. The 1-day σ's for each 2.5° latitude belt were averaged. For the daily average, the σ of 30 daily mean values was computed for each region and the σ's were averaged over a latitude belt.

Latitude zone	Pixel scale	Regional scale	Daily (regional scale)
42.5°N to 47.5°N	3.9 (8.3)	7.7 (3.1)	4.3 (3.5)
27.5°N to 32.5°N	2.7 (8.9)	4.1 (2.0)	6.5 (4.2)
2.5°N to 2.5°S	3.2 (6.3)	2.5 (1.8)	3.9 (3.2)
27.5°S to 32.5°S	4.0 (9.3)	2.4 (1.5)	5.5 (5.5)
42.5°N to 47.5°S	1.8 (4.5)	3.9 (2.0)	5.4 (4.6)

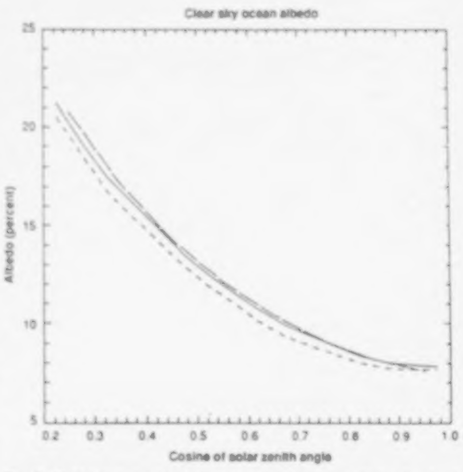


Fig. 2. Clear-sky ocean albedos. (solid line) Observed albedos for April 1985. The albedos were inferred from the scanner pixel data with the use of the operational ERBE algorithm for identifying clear-sky scenes. A total of 1,280,047 scanner pixels covering the global oceans was included. (Short dash) Same as the solid curve but, in addition to the operational algorithm, a stringent homogeneity criterion was used; a total of 50,640 pixels was included. (Long dash) Computed albedos from the model described in (10). In this model, observed ocean surface reflectivities are used in a multiple-scattering model that accounts for Rayleigh and aerosol scattering and absorption by O_3, H_2O, and CO_2.

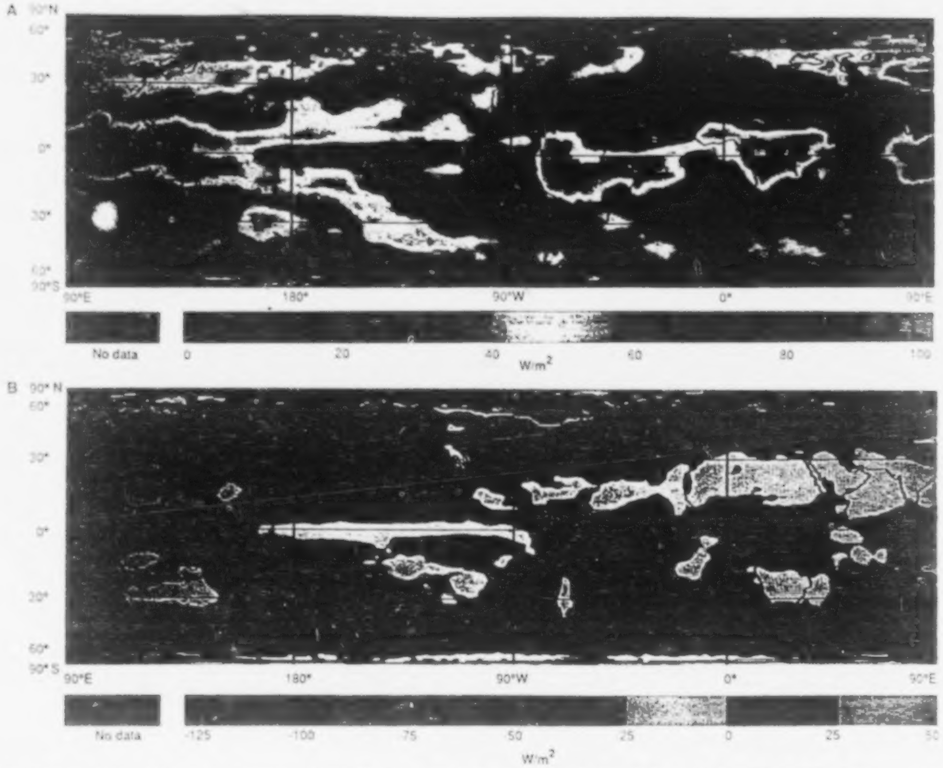

A
90°N
60°
30°
0°
30°
60°
90°S
90°E
180°
90°W
0°
90°E
No data
0
20
40
60
80
100
W/m^2
B
90°N
60°
30°
0°
30°
60°
90°S
90°E
180°
90°W
0°
90°E
No data
-125
-100
-75
-50
-25
0
25
50
W/m^2

Fig. 3. The LW (**A**) and SW (**B**) cloud forcing for April 1985. The uncertainties in the estimated values are about ± 10 W/m^2. Estimates over snow-covered regions may potentially have larger uncertainties because of difficulty in distinguishing clear from cloudy regions over the bright snow-covered regions.

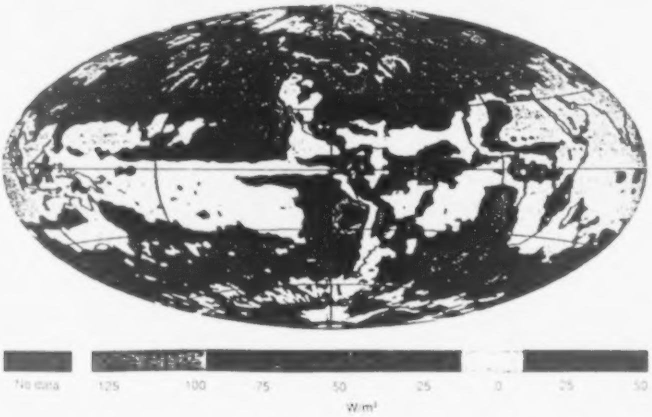

No data
125
100
75
50
25
0
25
50
W/m^2

Fig. 4. Net (C_{LW} + C_{SW}) cloud forcing for April 1985. The positive values of cloud forcing, including those seen in North America and in the polar regions, do not exceed 25 W/m^2.

Table 2. Global summary of radiation budget. Average incident solar radiation for April was 342 W/m²

Item	Albedo (%)	SW absorbed (W/m²)	LW emitted (W/m²)	NET heating (W/m²)
Clear sky	16.5	285.6	265.8	19.8
Average	29.5	241.1	234.5	6.6

Table 3. Comparison of global cloud forcing estimates in watts per meter squared.

	ERBE data (W/m²)				GCM's†
	April 1985	July 1985*	October 1985*	January 1986*	
C_{LW}	31.3	30	32	30.6	23 to 55
C_{SW}	−44.5	−46.4	−49.4	−51.9	−45 to −74
C	−13.2	−16.4	−17.4	−21.3	+1 to −34

*Analysis not completed for these months. †On the basis of a summary of six model studies (*16*) for model simulations with January and July boundary conditions.

and temporal scales (Table 1). The clear-sky σ's were always less than 10 W/m² (Table 1). In addition, sampling error for the monthly averaged regional estimates would be even smaller than the σ's shown in Table 1 (*11*). Thus, the statistics in Table 1 suggest that sampling errors for regional clear-sky fluxes are significantly smaller than the regional cloud forcing discussed below (*11*).

Errors in clear-sky fluxes can also arise from cloud contamination of the so-called clear scenes. Only data from instruments with much better resolution than the ERBE scanner can provide an accurate estimate of this bias error. Lacking such data, we attempted various consistency checks on a sample of the clear-sky fluxes to examine the size of the error. (i) We applied stringent homogeneity criteria in the identification of clear scenes. (ii) We chose scenes for which the eight surrounding scanner pixels were also clear. (iii) We adopted only those scenes for which the σ of the LW radiance was less than 1 percent of the mean LW flux for the nine pixels. The use of these criteria, chosen because of the results presented in (*12*), yielded lower albedos (Fig. 2) and larger LW fluxes than the general results for these scenes (Fig. 1). This response to editing of the data suggests that clouds did contaminate the operational data. However, the bias is only +0.8 percent for albedo and −4 W/m² for LW flux. The positive bias in the clear-sky albedo reduces the size of the negative SW cloud forcing. In contrast, the negative bias in the clear-sky LW flux reduces the size of the LW cloud forcing. Because the two forcing terms have opposite signs, the two bias errors partially cancel in the net cloud forcing (Fig. 2). The observed albedos are also consistent with those computed from a detailed theoretical model (Fig. 2) (*10*). The consistency between theory and observations builds confidence in the retrieved clear-sky fluxes. More detailed studies of scene identification errors with several alternative techniques (*7*) also gave results that were similar to those shown in Fig. 2.

LW and SW cloud forcing. The LW cloud forcing (Fig. 3A) reaches peak values over tropical regions and decreases toward the poles. In general, clouds reduce the LW emission to space. This reduction in emission is effectively an increase in the radiation energy absorbed in cloudy regions (compared with the energy in clear-sky regions). Because the reduction in the LW emission is largely a result of the emission from cold cloud tops, optically thick, high clouds reduce the emission more than low clouds. Hence, cloud forcing of 50 to 100 W/m² is at a maximum in regions with extensive cirrus cloud decks. Maxima occurred in three regions: (i) the tropical Pacific and Indian oceans surrounding Indonesia and the Pacific intertropical convergence zone north of the equator; (ii) the monsoon region in Central Africa and the deep convective regions of the northern third of South America; and (iii) the mid-latitude storm tracks in the Pacific and Atlantic oceans.

The SW cloud forcing (Fig. 3B) shows peaks in the mid-latitudes, unlike the LW forcing. In the tropics, large negative values were observed in the tropical monsoon and deep convective regions (Fig. 3A). These are areas where the LW forcing was equally large; the SW forcing was also large north of 30°N in the Atlantic and Pacific oceans. In these regions, the reduction of absorbed solar radiation as a result of clouds exceeded 100 W/m². Cloud systems associated with the mid-latitude storm tracks and extensive stratus decks over the colder oceans were responsible for this large reduction (*13*). Large (negative) values were also observed over the oceans in the mid-latitude Southern Hemisphere. These regions are known as the "roaring 40's" because of the persistence of cyclones. Both SW and LW cloud forcing were negligible over the narrow band of oceanic upwelling regions of the eastern and central Pacific oceans. In summary, cloud forcing patterns, even for observations during 1 month, reflect the major climatic regimes and the organized cloud systems of the planet. Distinguishing between clear and cloud scenes over the bright ice and snow-covered regions is difficult, and therefore the positive SW forcing results over and near the Arctic are less accurate than elsewhere; even the sign of the effect may be uncertain.

In tropical regions, where the clouds significantly affected the LW and SW fluxes, the LW and SW terms nearly cancel each other. The net forcing there (Fig. 4) was within ±10 W/m², roughly the estimated uncertainty in our regional estimates of the net cloud-radiative forcing. Between 15°N and 15°S, the zonally averaged forcing was slightly negative and was about 10 to 20 percent of the SW forcing. Earlier workers (*14*) anticipated the competing nature of the two forcing terms. However, their near cancellation is surprising. We do not understand the physical and dynamical constraints that require these cloud systems to organize in such a manner. The only exceptions to the near cancellation of the cloud forcing in the tropics are marine stratocumulus cloud systems. These systems commonly occur off the coast of Chile (in South America) and the coasts of Angola and Namibia in Africa.

Near cancellation of the column-integrated radiative forcing does not imply a negligible role of clouds in the regional climate. Modeling results (*6*) suggest that the negative C_{SW} is due to divergence (cooling) of SW flux at the earth's surface. In contrast, the positive C_{LW} in the tropics is due to convergence (heating) of LW flux in the troposphere. Thus these cloud systems may lead to a significant perturbation of the vertical gradients of radiative heating or cooling patterns (*6*, *15*).

Over the mid- to high-latitude oceans, poleward of 30° in both hemispheres, cloud forcing is negative. The negative forcing is particularly large over the Pacific and Atlantic oceans where C is between −50 and −100 W/m².

Another anomalous feature (Fig. 4) is the positive cloud forcing regions in the Western Sahara Desert and the Sahel regions of Africa. The positive values over the desert regions arise from the LW cloud forcing (Fig. 3), accompanied by negligible SW forcing. Cloud forcing is also positive over the snow-covered regions of Canada and the Arctic, where both the LW and the SW forcing terms are positive. However, as mentioned earlier, the clear-sky estimates over snow-covered regions are subject to large uncertainty. A better clear-sky discriminator and more extensive seasonal sampling are needed to confirm the forcing estimates over these regions.

Climatic implications. Cloud forcing reduces the absorbed solar radiation by 44.5 W/m² and the LW emission to space by 31.3 W/m² when averaged over the globe (Tables 2 and 3). Thus, globally, clouds reduce the radiative heating of the planet by 13.2 W/m^2 (Table 3). This conclusion is based on data from just 1 month. Data for July 1985, October 1985, and January 1986 are now being processed. Preliminary analyses of these months confirm the basic finding of this study: clouds have a net cooling affect on the global climate. There are significant month-to-month differences in the net cooling effect. It attained a maximum value of -21.3 W/m^2 in January 1986 (Table 3). The differences in the monthly values are a result of both seasonal and interannual variations in the parameters that govern cloud forcing. The data for the 4 months indicate the likely range of planetary radiative cooling due to clouds during a year.

Studies with GCM's provide some assessment of the climatic significance of this radiative cooling. Several studies have suggested that radiative heating of a mere 4 W/m^2 resulting from a doubling of CO_2 concentrations in the atmosphere would lead to a global warming of 3.5 to 5 K (*4*). The negative cloud-radiative forcing is three to five times as large as the doubled CO_2 forcing. The size of the forcing suggests that the planet would be significantly warmer without the current cloud-radiative forcing.

Cloud forcing has also been inferred from GCM's (*15, 16*). The GCM results are in qualitative agreement with those shown here. For both observations and models $C_{LW} > 0$, $C_{SW} < 0$, and $C < 0$. However, there are significant quantitative differences between the various models (Table 3) (*16*). The next step in identifying deficiencies in model simulations is to compare the regional and seasonal variations in the cloud forcing fields.

Cloud-climate feedback. A change in climate can perturb the cloud forcing, which in turn can feed back into the initial climate change. Thus, observations of long-term changes in cloud forcing can provide insights into the nature of the cloud-climate feedback. Two of the important feedback mechanisms suggested by our data are described below.

In mid- to high-latitude oceanic regions, strong negative forcing over the oceans coincides with regions of stratus and the storm tracks of mid-latitude cyclones. The frequency, as well as the latitudinal extent of these storms, couples to latitudinal temperature gradients (*13*). Large changes in the latitudinal temperature gradients accompany a climate change, such as the last ice age which occurred about 15,000 years ago (*17*). For example, during the glacial maximum, the mid-to-polar Atlantic Ocean was 5 to 10 K cooler than at present, while the subtropical oceans were less than 2 K cooler (*17*). In response to this enhanced temperature gradient and southward migration of the cold waters, the storm track clouds and the stratus decks might have shifted southward. Then, the regions where C was less than -50 W/m^2 would have also shifted southward and amplified the cooling. This mechanism is similar in principle to the ice-albedo feedback (*1, 4*). The effect of a shift from 45°N to 35°N of, for example, the -50 to -75 W/m^2 cloud forcing region is large. Such a shift, if it persists through the year, could induce a hemispherical average radiative cooling of roughly 3 W/m^2. This cooling is larger than the radiative effect of the observed decrease in CO_2 concentration from 300 to 180 ppm that occurred during the glacial maximum 15,000 to 20,000 years ago (*18*).

Tropical convective cloud systems contain a mixture of cumulus, cumulonimbus, and cirrus anvils (*19*). Despite the considerable discussion on the effect of tropical clouds, we still do not know whether the reflective cloud forcing of the cumulus clouds or the heating effect of the cirrus is dominant (*4, 5*). Our data suggest that these effects nearly cancel when integrated over the column. Some GCM's had anticipated this near cancellation of the LW and SW cloud forcing (*6*). However, these clouds can play a substantial role in climate change for two reasons: (i) The height of cloud tops largely governs the LW cloud forcing, but the water and ice content determine the SW forcing. (ii) Surface temperature influences the height but low-level convergence governs the water content. As an example, a warming due to the observed increase in CO_2 and other trace gases could increase the height of these clouds (*5*), which would increase C_{LW}. Because the individual forcing terms are large, a change in either of them would have a similar effect on the net cloud forcing.

In summary, the cloud forcing concept contributes to our understanding of climate and climate change. First, cloud forcing is an important part of the energy flow of the earth-atmosphere system. Second, we can quantitatively estimate cloud forcing from radiation budget measurements by broadband scanners. Third, we must be able to predict changes in cloud forcing if we are to predict the total response of climate to various perturbations. Such perturbations include orbital variations that have been implicated in earlier ice age episodes and changes that are expected from trace gas increases.

Observations of long-term changes in cloud forcing can be used directly to provide confirmation of previously untestable ideas (*5*) and climate model results (*4*) regarding climate change. For example, results from some GCMs suggest that severe drying of the mid-continental regions in North America and Europe could result from a doubling of the CO_2 concentrations (*4, 20*). In the Great Plains region of North America, the summer soil wetness in one model is decreased by 50 percent (*20*, figure 7), which suggests that a positive feedback between clouds and land surface could be a factor in soil drying (*20*). An initial tendency for drying causes decreased cloudiness, which leads to increased solar heating of the soil, thus amplifying tendency toward drying. The positive cloud feedback mechanism implies that the size of the (negative) SW cloud forcing would decrease significantly during a drought event. According to Manabe and Wetherald (*20*) the decrease could be as much as 25 W/m^2 in the Great Plains. The LW forcing should also decrease, but the model results suggest that changes in the SW cloud forcing dominate the feedback. Cloud forcing data could verify this postulated positive cloud feedback. For example, this mechanism would imply that the summertime SW cloud forcing over the Great Plains was anomalously low during the 1988 drought. Comparison of the cloud forcing for this year with the forcing for other years should confirm or refute this suggestion.

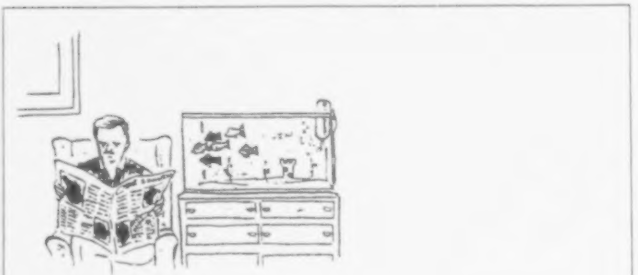
REFERENCES AND NOTES

1. R. D. Cess, *J. Atmos. Sci.* **33**, 1831 (1976); J. S. Ellis, thesis, Colorado State University, Fort Collins (1978). These are two of the earlier studies in which an attempt was made to assess the role of clouds from satellite radiation budget measurements. Ellis also estimated cloud-radiative forcing from regional radiation budget data. See S. H. Schneider [*J. Atmos. Sci.* **29**, 1413 (1972)] for a discussion of the cloud-climate feedback.
2. Cess and Ellis (*1*) estimated that the global greenhouse effect due to clouds was between 20 and 40 W/m^2. A hundredfold increase in CO_2 concentration would effectively trap about 25 W/m^2.
3. D. L. Hartmann *et al.*, *Rev. Geophys. Space Phys.* **24**, 439 (1986).
4. J. Hansen *et al.*, *Climate Processes and Climate Sensitivity*, Maurice Ewing Series (American Geophysical Union, Washington, DC, 1984), p. 130; C. A. Wilson and J. F. B. Mitchell, *J. Geophys. Res.* **92**, 13315 (1987); W. M. Washington and G. A. Meehl, *ibid.* **89**, 9475 (1984); R. T. Wetherald and S. Manabe, *J. Atmos. Sci.* **45**, 1397 (1988).
5. R. C. J. Somerville *et al.*, *J. Geophys. Res.* **89**, 9668 (1984); R. J. Charlson, J. E. Lovelock, M. O. Andreae, S. O. Warren, *Nature* **326**, 665 (1987).
6. V. Ramanathan, *J. Geophys. Res.* **92**, 4075 (1987).
7. B. R. Barkstrom, *Bull. Am. Meteorol. Soc.* **65**, 1170 (1984); ERBE science team (B. R. Barkstrom *et al.*), *ibid.* **67**, 818 (1986); R. B. Lee, B. R. Barkstrom, R. D. Cess, *Appl. Opt.* **26**, 3090 (1987).
8. The ERBS is in a midinclined orbit, which precesses through all local hours at the equator in 36 days. The NOAA-9 is in a sun-synchronous orbit with equatorial crossing times at 0230 and 1430 local solar time. This multisatellite configuration significantly reduces the temporal sampling errors in earlier satellite measurements. For example, see E. F. Harrison, P. Minnis, G. G. Gibson, *J. Spacecr. Rockets* **20**, 491 (1983).
9. Satellite radiation budget data are the traditional source for domain average values of F, α, and H [see T. H. Vonder Haar and V. E. Suomi, *Science* **163**, 667 (1969)]

We refer to these domain average values as cloudy-sky values. They are, in principle, a composite of clear and overcast sky values. To compute cloud forcing, we require both these cloudy-sky values and the clear-sky values. From the scanner pixels, we look for hole in the cloud cover. These holes we identify as the clear-sky scenes. Their fluxes give us the clear-sky values in each domain of 2.5° latitude by 2.5° longitude. (Further details of the clear-sky algorithms are given in B. A. Wielicki and R. N. Green, in preparation.)
10. B. P. Briegleb *et al.*, *J. Climatol. Appl. Meteorol.* **25**, 214 (1986).
11. A simple picture of the sampling error suggests that it should vary as $\sigma/\sqrt{N}$, where N is the number of independent samples. Typically, for a region 2.5° by 2.5°, over a period of 1 month, N should be about 10. The main point is that the sampling error should be smaller than the σ (Table 1) by a factor of 2 or more.
12. J. A. Coakley and F. P. Bretherton, *J. Geophys. Res.* **87**, 4917 (1982). This paper shows that the clear-sky LW radiance over the oceans is characterized by very low σ's.
13. E. Palmen and C. W. Newton, *Atmospheric Circulation Systems* (Academic Press, New York, 1969).
14. D. L. Hartmann and D. A. Short, *J. Atmos. Sci.* **37**, 1233 (1980); G. Ohring and P. F. Clapp, *ibid.*, p. 447.
15. T. D. Charlock and V. Ramanathan, *ibid.* **42**, 1408 (1985); A. Slingo and J. M. Slingo, *Q. J. R. Meteorol. Soc.* **114**, 1027 (1988).
16. R. D. Cess and G. L. Potter, *Tellus* **39A**, 460 (1987).
17. H. H. Lamb, *Climatic History and the Future* (Princeton Univ. Press, Princeton, NJ, 1985).
18. J. Jouzel *et al.*, *Nature* **329**, 403 (1987).
19. A. F. Bunker and M. Chaffee, *Tropical Indian Ocean Clouds* (East-West Center Press, Honolulu, HI, 1969).
20. S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **44**, 1211 (1987).

21. Supported in part by the NASA ERBE Project; NSF grant ATM8700286 (V.R. and E.A.). We thank the ERBE Science Team and the project scientists at NASA Langley Research Center for making this work possible, G. Gibson for the graphics, and two anonymous referees for their comments.

18 July 1988; accepted 28 November 1988



Unpleasant surprises in the greenhouse?

Wallace S. Broecker

There is now clear evidence that changes in the Earth's climate may be sudden rather than gradual. It is time to put research into the build-up of carbon dioxide in the atmosphere on a better footing.

THE inhabitants of planet Earth are quietly conducting a gigantic environmental experiment. So vast and so sweeping will be the consequences that, were it brought before any responsible council for approval, it would be firmly rejected. Yet it goes on with little interference from any jurisdiction or nation. The experiment in question is the release of CO_2 and other so-called 'greenhouse gases' to the atmosphere. Because these releases are largely by-products of energy and food production, we have little choice but to let the experiment continue. We can perhaps slow its pace by eliminating frivolous production and by making more efficient use of energy from fossil fuels. But beyond this we can only prepare ourselves to cope with its effects.

The task of scientists is to predict the consequences of the build-up of CO_2 and other gases. To be useful these predictions must be reasonably detailed, but we are in no better a position to make them than are medical scientists when asked when and where cancer will strike a specific person. Understanding the operation of the joint hydrosphere – atmosphere – biosphere – cryosphere system is every bit as difficult as understanding the factors that determine whether or not cancerous cells will get the upper hand. Because of our lack of basic knowledge, the range of possibility for the greenhouse effects remains large. It is for this reason that the experiment is a dangerous one. We play Russian roulette with climate, hoping that the future will hold no unpleasant surprises. No one knows what lies in the active chamber of the gun, but I am less optimistic about its contents than many.

My suspicion is that we have been lulled into complacency by model simulations that suggest a gradual warming over a period of about 100 years. If this seemingly logical response to a gradual build-up of greenhouse gases is correct, then one can imagine that man may be able to cope with the coming changes. While I do not have any complaints about how these modelling experiments were conducted — indeed they were done by brilliant scientists using the best computers available — the basic architecture of the models denies the possibility of key interactions that occur in the real system. The reason is that we do not yet know how to incorporate such interactions into models.

My impressions are more than educated hunches. They come from viewing the results of experiments nature has conducted on her own. The results of the most recent of them are well portrayed in polar ice, in ocean sediment and in bog mucks. What these records indicate is that Earth's climate does not respond to forcing in a smooth and gradual way. Rather, it responds in sharp jumps which involve large-scale reorganization of Earth's system. If this reading of the natural record is correct, then we must consider the possibility that the main responses of the system to our provocation of the atmosphere will come in jumps whose timing and magnitude are unpredictable. Coping with this type of change is clearly a far more serious matter than coping with a gradual warming.

> **"We play Russian roulette with climate [and] no one knows what lies in the active chamber of the gun . . ."**

For more than 100 years scientists have been aware that the Earth is in the midst of a series of cyclic glaciations. Oxygen isotope measurements made on microscopic shells from deep-sea sediments provide a continuous record of these events. They show that cycles averaging 100,000 years in length carried us from warm climates, comparable to today's, to the cold climates of full glacial time. Power spectra for these records point a finger at cycles in the Earth's orbital characteristics as the driving force[1,2]. Seasonality was at times stronger and at times weaker than it is today. Although most scientists now accept the orbital hypothesis, none of the mechanisms that have been proposed to explain the linkage between seasonality and climate is universally accepted. This matter is the subject of much research.

The ^{18}O/^{16}O record in deep-sea cores gives the impression that the response of the climatic system to orbital forcing is smooth and gradual (Fig. 1 — see over). Only recently have we begun to realize that this impression is a false one. One of the early clues came from studies of the ecology of the remains of planktonic organisms contained in deep-sea cores of rapidly accumulated sediment from the North Atlantic[3]. The ecological changes recorded in these cores probably reflect changes in surface-water temperature. This record does not show the gradual change scientists had become accustomed to. Instead it shows an abrupt end to glacial time and, even more interesting, a brief period of intense cold interrupting the warm period that followed (Fig. 1). Although the two records shown in Fig. 1 are quite different, they are not incompatible. Changes in ^{18}O/^{16}O in the shells of marine sediments are largely the result of the waxing and waning of the ^{18}O-deficient continental ice caps. As the response time of global ice caps is thousands of years, the ^{18}O record smooths out the rapid changes in climate.

It took more than this, however, to make us take these abrupt changes seriously. The evidence that turned our heads came from holes drilled through the Greenland ice cap. As a foot or so of ice forms from each year's snowfall, the record captures changes in the ice-cap environment no matter how rapid they have been. These changes are recorded in the ratio of isotopically 'heavy' to isotopically 'light' water in the ice (a measure of air temperature)[4,5], in the content of particulate matter in the ice (a measure of the dustiness of the air over the ice cap)[6] and in the content of CO_2 and other greenhouse gases contained in the air trapped as bubbles in the ice (a measure of the atmosphere's greenhouse capacity)[7]. Like the ecological record in deep-sea muds from the North Atlantic, the ice core records from Greenland give a dramatically different impression of the manner in which climate changes than do the oxygen isotope records for marine shells. They show that during glacial time climate changed frequently and in great leaps. The typical leap involves a 6°C change in air temperature, a fivefold change in atmospheric dust content and a 20% change in the CO_2 content of air. In cold times the air was dustier and contained less CO_2.

While the record in Greenland's ice shows that climate can change in big leaps, we have to look further for a clue as to why these leaps occur. The last of the events seen in the Greenland record is well documented not only in Greenland ice and in North Atlantic sediment, but also in lake and bog sediments from throughout Western Europe and maritime Canada[8]. On land it is recorded by large shifts in the ecology of plants (as recorded by their pollen grains). During warm periods trees grew in these areas; during cold periods the trees were replaced by tundra shrubs. Although this last of the Greenland events is found in bog and lake sediments throughout northern Europe, it is not seen in similar records from the United States. This geographical distribution suggests the North Atlantic Ocean as the culprit. Based on this clue, we are beginning to see how devilish are the links between components of the climatic system.

Rather than responding smoothly to gradual forcing, the ocean–atmosphere system appears to respond by changing the way it works. India's climate provides an apt analogy. The winters in India are very dry because of the descent of cold air from the Tibetan plateau. Summer heating causes this atmospheric circulation pattern to reverse abruptly. Air rises from the Tibetan plateau, drawing oceanic air across the Indian subcontinent, and the dry conditions give way to monsoonal rains.

The Earth's climatic system currently works in a way beneficial to northern Europe[9]. This region is warmed by heat released from the surface waters of the North Atlantic. The amount is a staggering 30% of that received by the North Atlantic from the Sun! This heat is steadily carried northward, as on a conveyor belt, by the ocean circulation system. In the vicinity of Iceland the warm water meets cold air. The air warms and ameliorates climate on the adjacent land. The water cools, sinks to the abyss and flows as a great river, down the full length of the Atlantic, around Africa, through the southern Indian Ocean and finally up the Pacific Ocean (Fig. 2). This current carries 20 times more water than the world's rivers combined.

In the North Pacific the ocean conveyor belt runs just the other way round. Deep waters move towards the north and rise to the surface and then flow towards the Equator in the upper ocean. So in today's world, the Atlantic conveyor belt carries tropical heat for delivery to the atmosphere at high northern latitudes, while the Pacific conveyor belt forces cold surface waters to move southward, pushing the invading warm waters back towards the Equator.

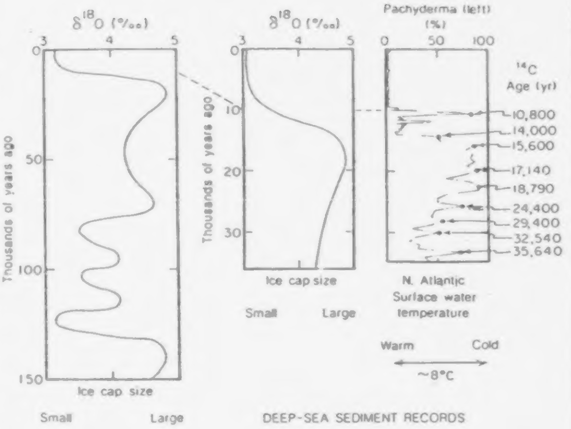


Fig. 1 The ratio of heavy oxygen (^{18}O) to light oxygen (^{16}O) in foraminifera shells preserved in deep-sea sediments provides our best record as to how the great continental ice sheets of the Northern Hemisphere waxed and waned. The reason is that the snow that builds ice caps is depleted in the heavy oxygen isotope. Therefore as ice caps grow, the ocean is correspondingly enriched in heavy oxygen. So also is the oxygen in the calcium carbonate of shells living in these waters.

The oxygen isotope record on the left covers just over one major climate cycle. There have been eight such cycles in the past million years. The diagram in the middle is an enlargement of that on the left, designed to emphasize that these oxygen isotope records indicate a gradual and smooth transition from full glacial to full interglacial conditions. Recent findings demonstrate that this view of natural climate change is misleading. The sluggish retreat of the ice and blurring of the record by burrowing worms combine to give what proves to be the wrong impression.

On the right is the record from a deep-sea sediment obtained west of the British Isles. This record is based on the abundance of the shells of the planktonic herbivore *Pachyderma* (left coiling) which lives in waters adjacent to Greenland. It is the only species of planktonic foraminifera found in these icy waters. During cold periods this species dominated the entire North Atlantic, providing up to 90% of the shells found in the sediments off Britain.

As can be seen, this record tells a different story. The North Atlantic warmed abruptly about 15,000 years ago, and has so remained (except for two brief cold relapses) until the present. It is the abruptness of the warming and of the two brief and intense epochs of renewed cold that are of great interest. The second of these cold epochs was first recognized from study of the pollen records in bogs created in northern Europe during the retreat of the last great ice sheet. These records show that the forests which repopulated this area after ice departed were destroyed by a brief and intensely cold interval of several hundred years' duration. They were replaced by the shrubs of glacial time.

Why does our ocean operate in this fashion? Although we don't have the complete answer, we do have the first principle. The circulation system is governed by salt. Because of the difference in the circulation patterns, surface waters in the North Atlantic are on average warmer than those in the North Pacific. This allows more water to evaporate from the North Atlantic than from the North Pacific, and in turn gives rise to a net transport of water vapour through the atmosphere from the Atlantic to the Pacific. The North Atlantic is enriched in salt by this process (and the North Pacific waters correspondingly diluted). The enrichment of salt in the North Atlantic must somehow be compensated by a flow of salt through the sea from Atlantic to Pacific. The compensation in today's ocean is achieved by the flow of a deep current of salty water from the Atlantic to the Pacific and a matching flow of correspondingly less salty water around the other way in the upper ocean.

The phenomenon that maintains this situation is, I suspect, a potentially dangerous one. The circulation pattern is self-reinforcing and hence self-stabilizing. The deep current is driven by the extra density supplied to the waters of the North Atlantic by the enrichment of salt. The enrichment of salt is driven by the heat carried by the warm water which flows northward in the upper Atlantic to supply the deep current. A classic chicken and egg situation! Excess evaporation causes the deep current; the deep current causes excess evaporation.

What are the consequences of perturbation of this system? Palaeoclimatic evidence points to a shutdown of the North Atlantic conveyor belt during glacial periods. Such a shutdown would cool the North Atlantic and its adjacent lands by 6–8°C. This is turn would cause the boreal forests in these areas to give way to tundra shrubs. The sparsity of vegetation would permit far more dust to be lifted into the atmosphere. Finally, the only feasible mechanisms scientists have come up with to explain rapid changes in the atmosphere's CO_2 content involve modifications in the ocean's circulation pattern and intensity. Thus we surmise that the reorganization of ocean circulation that accompanied the shutdown of deep-water production in the North Atlantic produced all of the environmental changes recorded in ice cores. The many leaps in climate seen in the glacial part of the Greenland ice core records probably represent flips of the system back and forth between two self-stabilizing modes of operation.

It must be emphasized that the leaps in climate seen in the ice and sediment records for the North Atlantic region were confined to the cold parts of the climatic cycle. Following the transition from cold to warm conditions 10,000 years ago, the climate in this region has remained remarkably constant. Apparently Earth's climatic system has remained firmly locked in its present mode of operation. If so, what is the likelihood that increases in CO_2 and other greenhouse gases will jolt the ocean–atmosphere system out of its current mode into one more suitable to the coming conditions?

Unfortunately, we have little basis for answering this critical question. Nature provides us with no recent analogy to the super-interglacial conditions we are about to generate. The climate of the past 10,000 years is representative of the warmest part of the last several glacial cycles. Hence nature has not explored the super-interglacial climatic regime (at least not in sufficiently recent times that our geological records give an adequate picture of Earth's environment to be useful for future prediction). Further, as we have only recently become aware of the complexity of the linkages which tie together ocean, atmosphere, ice and terrestrial vegetation, we have not even begun to formulate means by which these linkages might be modelled. Indeed, reliable modelling may never be possible.

If we are to get into a position to cope with the effects not only of the greenhouse gases, but also of the various poisons being released to the environment, we must greatly expand our efforts to understand the individual parts of the Earth's great surface system and the interactions among them. The task, however, is every bit as complex as that of preventing cancer.

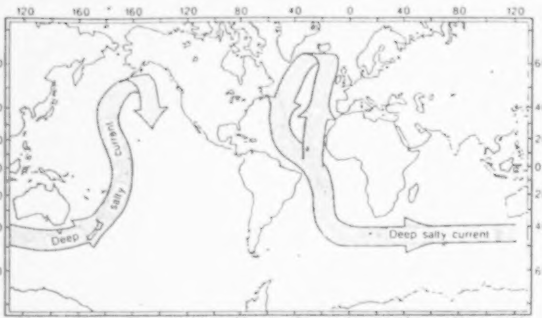


Fig. 2 A large-scale salt transport system operates in today's ocean to compensate for the transport of water (as vapour) through the atmosphere from the Atlantic to the Pacific Ocean. Salty, deep water formed in the North Atlantic flows down the length of the Atlantic, around Africa, through the southern Indian Ocean and finally northward in the deep Pacific Ocean. Some of this water upwells in the North Pacific, bringing with it the salt left behind in the Atlantic due to vapour transport. This atmospheric water vapour and ocean salt transport system is self-stabilizing. Records from ice and sediment tell us that this great conveyor system was somehow disrupted during glacial time and replaced by an alternative mode of operation.

I see no hope of getting much done in the United States without a fundamental reorganization of our approach to environmental research. I believe that most scientists would agree that the handling of research on greenhouse effects by the Department of Energy and on acid rain by the Environmental Protection Agency has been ineffective. The problem lies partly in the perception by the managers of these programmes that their mandate is to obtain quick fixes, and partly in their inability to grasp the subtleties of the problems placed under their jurisdiction. The result is that these managers avoid long-term strategies designed to build up our base of knowledge. Rather, they are strongly attracted by proposals to re-work existing information even though most scientists agree that it has been squeezed nearly dry. Thus, while the existing programmes serve to keep management informed, they do little to further our ability to predict the consequences of our actions. It is as if the efforts to prevent cancer were based largely on epidemiological information with no biochemical or cellular research. If we are to get out of this rut, the responsibility for basic research on environmental systems must be wrested from these mission-orientated agencies and given instead to an organization which is dedicated to basic research and is isolated from immediate political pressures.

As it now stands, a healthy component of basic research is being carried out only in those areas where there is a strong tradition of federal sponsorship (that is, the atmospheric and ocean sciences). Research on the continental parts of the environmental system (vegetation, soils and waters) remains in the Dark Ages. It's a Catch-22 situation — managers at the National Science Foundation (NSF) feel that basic research in these areas should be sponsored by the appropriate mission-orientated agency, but such agencies shun basic research.

Unique opportunities to expand our knowledge of environmental systems slip by without being fully exploited. A prime example is the invasion of man-made tracers (that is, nuclear-testing tritium and radiocarbon, reactor radiokrypton and industrial freons) into the sea. A detailed knowledge of the patterns and rates of movement of these substance through the sea will prove a tremendous boon to the validation of general circulation models for the atmosphere–ocean system. Although the atmospheric side of such models is fully developed, the oceanic side is still in a primitive state. Further development is hampered by our lack of knowledge of the physics of key processes occurring in the sea. Because of this, ocean models of adequate sophistication are decades away. Despite the obvious value of tracer data, the efforts to map the passage of these substances through the sea's interior are sparse. NSF is concerned that surveying brings too little immediate scientific yield, while the mission-orientated agencies fail to appreciate the fact that if we are to understand the Earth's system we must adopt long-term strategies. With the exception of the French, who have developed a remarkably good tracer programme in the Indian Ocean, other industrial countries have shown no greater interest in ocean tracers than had the United States. Hence future ocean modellers will rue the deficiencies in the documentation of man's great ocean-tracer experiment.

I am not suggesting that things could

be altered simply by increasing NSF's budget. NSF is not set up to put strings on the use of its funds. Nor should it be. But to do the kind of research that will be required if we are to deal effectively with long-term environmental problems, there must be some strings.

In this time of budget deficits it may be unrealistic to call for new government entities, but I am convinced that the only way to straighten out the mess in environmental research is to create a new national institute. This institute would have two objectives. First, it would sponsor environmental research; second, it would advise the government on a broad range of environmental questions.

The International Committee of Scientific Unions has recently given its blessing to a new initiative in environmental science, the International Geosphere–Biosphere Program (IGBP). The aim is to further our understanding of the operation of the individual elements of the environmental system and of the linkages between them. The mission-orientated agencies in the United States are already planning how to capture their share of this new pie. Judging by past performance, it would be a mistake to let them have any of it. Instead, the US monies to be spent on IGBP should be funnelled through a new entity, The National Institute for the Environment. The primary responsibility of this institute would be to develop integrated programmes dedicated to furthering our knowledge of environmental systems. In particular, the Institute would focus on those areas that most need attention, namely, the continental components of the climatic system. The programmes would be planned by the most capable scientists in the country and conducted in the most appropriate laboratories (university, industry and government). The institute would be overseen by a board of trustees, consisting of eminent scientists. Its director, chosen by this board, would be a highly capable scientist, skilled in management. While the institute would have its own in-house scientific staff, most of its resources would go towards the funding of external activities.

There are isolated success stories. For example, two NASA managers, Shelby Tilford and Bob Watson, are running a programme designed to determine the sources of atmospheric methane and how the strengths of these sources have changed with time. This programme is a beautiful example of how environmental research should be conducted. It was designed by the nation's most knowledgeable scientists and is being carried out by highly capable groups throughout the country. The cost is modest, about two million dollars a year, and the payoff will be large. It works because Watson and Tilford are themselves outstanding scientists who know what the tractable problems are and where the intellectual resources to tackle them reside.

Most of the research of the new institute should be housed in universities. It is in such settings that excellent research is generated for a minimum cost. By placing graduate education and research under one roof, an optimum environment for both is created. With a few exceptions, environmental research in large laboratories operated by government agencies has, in my opinion, proved to be unproductive and wasteful.

There are, however, two tasks that clearly require facilities not available to universities. One involves satellite observations, which will be the cornerstone of the effort to monitor the climatic system. Such platforms are best operated by NASA. The other is large-scale climate modelling, which is now the basis for all climate prediction. These facilities require large research staffs and immense computer power. Fortunately, a successful format has already been found which involves cooperation between universities and government departments. The National Oceanic and Atmospheric Administration has its primary effort on Princeton's campus. NASA bases such an effort on Columbia's campus. NSF operates such an effort at its National Center for Atmospheric Research in Boulder, Colorado. Because of the great importance of the so-called 'general circulation models' to climate prediction, these existing laboratories should be strengthened. Also, similar efforts must be launched in other university settings.

"Not only do our current managers lack a proper intellectual grasp of the problem, but they are obsessed with legislatively imposed 'five-year reports', and give little attention to developing a long-term strategy to build the needed base of knowledge."

Five specific areas in which research must be greatly expanded can be singled out for special attention: (1) the large-scale circulation of the ocean; (2) the processes regulating soil moisture; (3) the processes responsible for cloud formation; (4) the role of biogeochemical processes on the atmosphere's composition; (5) the processes regulating sea ice.

Of course, there are already research programmes in these areas, but in my estimation they will not come up with answers quickly enough. In each area we need major new observational programmes to supply the key data that are necessary to develop a better physical understanding. In each area we need a cadre of young scientists with the appropriate training.

We also have to intensify our study of the climatic changes that have taken place over the past 100,000 years. As discussed above, nature herself has conducted large-scale climatic experiments. The response of the system to these natural experiments is recorded in sediments and in ice. By study of these records, we will be able to learn valuable lessons about the interactions that link the various elements of Earth's system together. I should stress once again that it is changes in these linkages which are likely to carry the greatest threats.

Although we don't know nearly enough about the operation of the Earth's climate to make reliable predictions of the consequences of the build-up of greenhouse gases, we do know enough to say that the effects are potentially quite serious. Whatever happens, it seems to me that the Earth's remaining wildlife will be dealt a serious blow. If, as the climatic record in ice and sediment suggests, changes in climate come in leaps rather than gradually, then the greenhouse build-up may threaten our food supply. To date, we have dealt with this problem as if its effects would come in the distant future and so gradually that we could easily cope with them. This is certainly a possibility, but I believe that there is an equal possibility that they will arrive suddenly and dramatically.

To prepare ourselves, we must take the problem of climatic change as seriously as we take those of cancer and nuclear defence. There are no easy solutions, and we must gear up for the long, hard job of working out how Earth's climate operates. To do this will require not only more financial and human resources, but also the administration appropriate to the task. Not only do our current managers lack a proper intellectual grasp of the problem, but they are obsessed with legislatively imposed 'five-year reports', and give little attention to developing a long-term strategy to build the needed base of knowledge. Even with a great intensification of effort, I fear that the effects of the rise in concentration of the greenhouse gases will come largely as surprises. But the greater our knowledge, the greater the wisdom that will be brought to bear if surprises do come. ☐

1. Hays, J.D. *et al. Science* **194**, 1121–1132 (1976).
2. Imbrie, J. *et al. Milankovitch and Climate* Part I (eds Berger, A.L. *et al.*) 269–305 (Reidel, Dordrecht, 1984).
3. Ruddiman, W.F. & McIntyre, A. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 35, 145–214 (1981).
4. Dansgaard, W. *et al. Science* **218**, 1273–1277 (1982).
5. Dansgaard, W. *et al.* in *Green Ice Core: Geophysics, Geochemistry and the Environment* (eds Langway, C.C. *et al.*) *Am. Geophys. Un. Monogr.* No. 33, 71–76 (1985).
6. Hammer, C.U. *et al.* in *Green Ice Core: Geophysics, Geochemistry and the Environment* (eds Langway, C.C. *et al.*) *Am. Geophys. Un. Monogr.* No. 33, 90–94 (1985).
7. Stauffer, B. *et al. Ann. Glaciol.* 5, 160–164 (1984).
8. Rind, D. *et al. Climate Dynamics* 1, 3–33 (1986).
9. Broecker, W.S. *et al. Nature* 315, 21–25 (1985).

Wallace S. Broecker is at the Lamont–Doherty Geological Observatory of Columbia University, Palisades, New York 10964, USA.

Systems Research Vol. 5, No. 3, pp. 225–240, 1988.
Printed in Great Britain.

0731-7239/88 $3.00 + 0.00
Pergamon Press plc
© 1988 International Federation for Systems Research

The Need for Systems Research on Global Climate Change

FRED B. WOOD, Jr*

Office of Technology Assessment, United States Congress, Washington, DC 20510,
U.S.A.

(*Received* 25 *April* 1988)

Key words—Climate change; greenhouse effects; earth sciences; complex systems; feedback loops; interdisciplinary research.

Abstract—Recent research has documented the immense complexity of global climate change. The climate system (1) is characterized by multiple inputs and feedback relationships involving many components of the earth system that (2) operate on variable time and geographic scales and (3) can exhibit nonlinear and counterintuitive behavior leading to (4) possibly abrupt changes in equilibrium conditions. Unprecedented rates of increase in atmospheric trace gases and deforestation justify intensive systems research to help verify current and projected global warming trends. This systems review identified numerous uncertainties that warrant attention.

INTRODUCTION

SYSTEMS researchers have for decades recognized that, at least in principle, the physical and biological earth can best be understood as a system with many of the same generic behavioral characteristics as engineering, management, neural, or ecological systems [13, 94, 95, 147]. Climate researchers have likewise recognized that, in principle, climate can best be described, modeled, and researched as part of the broader earth system [47, 70, 137]. However, until relatively recently, climate change (e.g. changes in average temperature, precipitation, humidity, and the like over a period of years to decades) has been researched largely from a limited, disciplinary perspective. Much of the early research on climate change focused primarily on monitoring and modeling of the atmosphere, with much less attention to other key components of the earth system, because little was known about other key variables and because climate research was still conducted largely within the discipline of atmospheric science rather than the multidisciplinary earth sciences.

Over the last decade, and especially the last few years, three trends have converged. The first is a rapid, exponential increase in scientific knowledge about previously unrecognized and/or poorly understood relationships between the atmosphere and other components of the earth system, notably the cryosphere (snow and ice), oceans, biomass (especially forest cover and ocean plankton), land surface albedo, tectonic processes, and solar irradiance. Second is the emergence of a strong consensus on the need for a broader earth systems perspective as a guide for research on global climate change and related areas, as reflected in initiatives such as the International Geosphere–Biosphere Program and the global geoscience programs in the United States [123, 134, 141]. Third is the rapidly accumulating evidence that anthropogenic changes to the global environment are already at unprecedented levels, especially with respect to increases in atmospheric trace gases such as carbon dioxide and with respect to decreases in forest cover.

Despite these trends, the systems research community has yet to be mobilized as an effective participant in the climate research enterprise. The purpose of this article is to demonstrate why climate change is manifestly one of the most complex and challenging scientific problems to confront the systems research community. The article provides a systems review of selected relevant research, identifies and describes key uncertainties, and discusses some possible priorities for systems research on climate change.

CLIMATE AS A COMPLEX SYSTEM

The dominant characteristic of climate change is its complexity. By any measure of systems complexity (e.g. number of key variables, feedback loops, inputs, and outputs), climate rates as a very complex system. This is exemplified by the heavy use of computerized models as a climate research tool. As knowledge about climate change has increased along with the computational capacity of computers, researchers have built more complexity into the models by including additional variables and feedback loops and by adding greater resolution to the input data and calculations. The largest of these climate models (known as general circulation models or GCMs) are pushing the limits of existing supercomputer capacity but still fall short of fully representing the climate system. The complexity of scientific knowledge about the climate system appears to be increasing as fast or faster than the ability to model the system on computers.

---

* The views expressed are those of the author and not necessarily those of the OTA, Technology Assessment Board, or U.S. Congress. This article is based on independent research of the author and not on work conducted for the OTA.

State-of-the-art reviews of the major climate models (defined here as the GCMs; see, e.g. [56, 145, 152, 158]) have found that most model results agree on a 3 ± 1.5°C (that is, 1.5–4.5°C) projected global warming for a CO_2 doubling, although with significant disagreements on the regional distribution of changes in temperature, precipitation, and soil moisture [118, 121]. These reviews have identified numerous areas of uncertainty, such as clouds, sea ice, and surface albedo, and have typically concluded that '[e]ven the most comprehensive global climate models greatly oversimplify or misrepresent key climate processes' ([130]; also see [35, 60, 118, 121]). And over the last two or three years, substantial new scientific knowledge has developed that has only begun to be incorporated in the climate models.

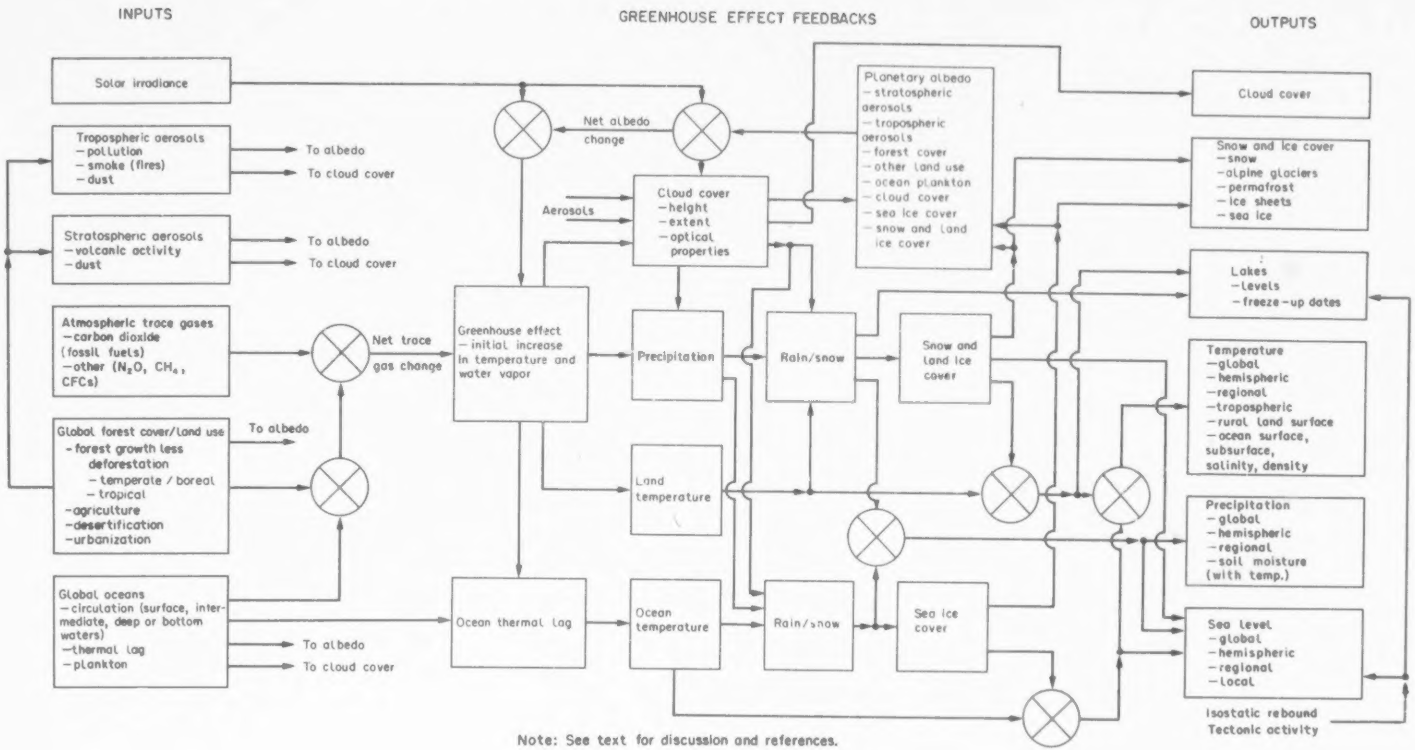
I have attempted to illustrate the complexity of the climate system with respect to the greenhouse effect in the conceptual model shown as Fig. 1. This model captures the results of just some of the recent scientific research that appears to be relevant to climate change. A complete synthesis of all relevant research is well beyond the scope of this paper (see [134] for a conceptual model that includes more variables and relationships; for other related conceptual models, see [47, 70, 113]). Also a more complete model could show far greater complexity by reflecting the atmospheric and ocean dynamics and global geographic grid points now incorporated in the GCMs. Several aspects of Fig. 1 are discussed in more detail below.

CLIMATE SYSTEM INPUTS

As shown in Fig. 1, the climate system includes multiple inputs that can collectively have a highly variable direct and indirect impact. Key inputs include: the atmospheric concentration of carbon dioxide (reflecting in large part the level of fossil fuel consumption as a CO_2 source and the role of global forest cover and oceans as CO_2 sinks) and other trace gases; stratospheric aerosols (largely from volcanic eruptions); tropospheric aerosols (e.g. from pollution, fires, biological emissions, and dust); solar irradiance (reflecting both solar and orbital factors); and ocean thermal lag. These are all considered inputs in the sense that in the short run (years to decades) they are thought to be independent of climate. In the longer-term, climate change itself could affect some of these inputs, such as forest cover (and other biomass as a CO_2 sink), patterns and levels of fossil energy use (as a CO_2 source), and ocean circulation patterns (and the ability of the oceans to sequester heat and store carbon), and, in the very long-term (centuries to millenia), the level of volcanic activity as influenced by the impact of the changing weight of the continental ice sheets on tectonic activity. Thus, while not shown in Fig. 1, long-term feedback loops likely exist between the output of the climate system and the inputs as defined above.

The direct effect of these inputs is to determine the level of solar radiation reaching the surface of the earth and trapped in the lower atmosphere, all other things being equal. This is the greenhouse effect whereby increasing CO_2 and other radiatively active trace gases are essentially transparent to incoming solar (short-wave) radiation and partially block or trap outgoing terrestrial (long-wave) radiation from being emitted back to space. The increased net heat input to the lower atmosphere in turn raises the temperature and water content (humidity) of the air and ultimately increases precipitation as well as temperature. This is the theoretical basis for the global greenhouse warming projected by the GCMs to take place as the atmospheric concentration of CO_2 (and other trace gases) continues to increase.

Most climate models typically assume all of these inputs to be constant, with the exception of CO_2, which is usually assumed to continue to increase at roughly 0.3–0.5% yr. Changes in the other inputs could amplify or partially offset the effects of rising CO_2. For example, a reduction in solar radiation and/or increase in stratospheric volcanic aerosols would offset some of the CO_2-induced warming, all other things being equal. Climate models generally assume an unchanging solar constant. But satellite data for the last eight yr indicate a measureable downward trend in solar irradiance of roughly 0.013%/yr (about 0.1% over the 1979–1986 time frame), which could be quite significant if the trend continues [160]. The cause of this trend is not well understood, nor is the likelihood of it extending over several decades (see [143] for discussion of possible correlation with sunspot cycles and changes in solar diameter).


INPUTS
GREENHOUSE EFFECT FEEDBACKS
OUTPUTS
Solar irradiance
Tropospheric aerosols
— pollution
— smoke (fires)
— dust
To albedo
To cloud cover
Stratospheric aerosols
— volcanic activity
— dust
To albedo
To cloud cover
Atmospheric trace gases
— carbon dioxide
(fossil fuels)
— other (N_2O, CH_4, CFCs)
Net trace
gas change
Global forest cover/Land use
- forest growth less
deforestation
- temperate / boreal
- tropical
- agriculture
- desertification
- urbanization
To albedo
Global oceans
— circulation (surface, intermediate, deep or bottom waters)
— thermal lag
— plankton
To albedo
To cloud cover
Net albedo
change
Aerosols
Cloud cover
— height
— extent
— optical
properties
Planetary albedo
— stratospheric
aerosols
— tropospheric
aerosols
— forest cover
— other land use
— ocean plankton
— cloud cover
— sea ice cover
— snow and land
ice cover
Greenhouse effect
— initial increase
in temperature and
water vapor
Precipitation
Rain/snow
Snow and
land ice
cover
Land
temperature
Ocean thermal lag
Ocean
temperature
Rain/snow
Sea ice
cover
Cloud cover
Snow and ice cover
— snow
— alpine glaciers
— permafrost
— ice sheets
— sea ice
Lakes
— levels
— freeze-up dates
Temperature
— global
— hemispheric
— regional
— tropospheric
— rural land surface
— ocean surface,
subsurface,
salinity, density
Precipitation
— global
— hemispheric
— regional
— soil moisture
(with temp.)
Sea level
— global
— hemispheric
— regional
— local
Isostatic rebound
Tectonic activity

Note: See text for discussion and references.

Fig. 1. Illustrative conceptual model of the climate system.

Trends in volcanic aerosols are also uncertain. When injected into the stratosphere, these aerosols can partially block incoming solar radiation, and can have a short-term (e.g. 1–2 yr) climatic cooling effect at the surface of about 0.3–0.4°C [110, 124]). The level of volcanic activity, and especially of major eruptions, appears to be variable but on the average to have increased over the last few decades compared to the earlier half of this century. But this recent trend is suspect due to increasing yet still incomplete monitoring, and is well within the range of long-term variability [18, 127].

While increasing stratospheric aerosols appear to contribute to climatic cooling, increasing tropospheric aerosols from pollution, smoke, dust, and the like are thought to result in cooling or warming, depending on the size, height, and optical characteristics of the aerosol [30, 131]. While total tropospheric aerosols appear to be increasing from multiple sources (including fossil fuel consumption, agricultural cropping, forest fires, and desert sand and dust storms), the global aerosol distribution and expected climatic effects are not known. A further complicating factor is the poorly understood role of tropospheric aerosols in cloud formation, in itself another major source of uncertainty to be discussed later.

The final input to be considered here is ocean thermal lag. The oceans sequester heat and thus serve to buffer changes in air temperature whether caused by CO_2-induced greenhouse effects or other factors. Since the oceans cover about three-quarters of the globe, much of the temperature changes could be delayed for decades. Common estimates of ocean thermal lag range from 10 to 100 yr, depending on the thermal sensitivity of the coupled atmosphere–ocean system [57, 119, 120]. The major climate models assume that whatever value of ocean thermal lag is used it will remain constant. Recently, however, the possibility of abrupt (years to decades) nonlinear changes in ocean circulation patterns has been raised [20], with an as yet unknown effect on ocean thermal lag and climate.

CLIMATE SYSTEM FEEDBACKS

The focus here is on very short-term (days to years) feedback loops in the climate system. Several major feedback loops are illustrated in Fig. 1. Three of these—clouds, snow and ice, and total planetary albedo—are discussed below.

Clouds are recognized as one of the least well understood but potentially among the most significant feedback components of the climate system and the greenhouse effect. In 1982 and 1983, U.S. National Research Council studies [138, 139] noted that '[i]n view of the uncertainties in our knowledge of cloud prediction schemes in existing climate models, it is premature to draw conclusions regarding the influence of clouds on climate sensitivity to increased carbon dioxide.' Since then, the emerging scientific evidence suggests that clouds can have a positive or negative feedback effect, depending on cloud height and optical properties (e.g. optical thickness, albedo, water content). Like tropospheric aerosols, the effect of clouds on climate depends on whether more radiation is trapped in the troposphere than screened out, which results in a net increase in radiation and a net warming, or vice versa. For example, one scenario is that low, thick clouds act as a negative feedback and increase albedo (or reflectance) with a relative cooling effect while high, thin clouds act as a positive feedback and decrease albedo with a relative warming effect. Assumptions about cloud dynamics as well as cloud cover (see below) can have a significant effect on the behavior of climate models, such that greenhouse warming could be greatly amplified or reduced [24, 86, 114, 118, 121, 122, 128, 129].

In addition to cloud dynamics for any given or prescribed amount of cloud cover, there is the question of whether cloud cover would change markedly as a result of the greenhouse effect, in terms of either the type or extent of cloud cover. The possible complexities are only beginning to be identified. For example, one suggestion is that ocean warming could stimulate emissions of dimethylsulphide from phytoplankton which could in turn increase cloud-condensation nuclei and decrease cloud droplet sizes; this could then translate into an increase in albedo and a relative cooling effect [11, 25]. Data on global cloud cover trends do not exist, but are under development in the International Satellite Cloud Climatology Program [117]. Data on cloud cover for the U.S. indicate increasing cloud cover in recent decades [4, 125], which would appear to be consistent with the reported upward trend in precipitation [19].

Snow and ice are recognized as another important feedback component of the climate system, in part because of their effect on planetary albedo. Any increase (or decrease) in snow and ice cover would increase (decrease) albedo and act as a positive feedback, all other things being equal. Until recently, it was generally assumed that the areal extent of snow and ice was inversely correlated with temperature, and that a warming trend would result in reduced snow and ice (and thus reduced albedo) and vice versa. However, research results have confirmed earlier theoretical studies that a warming trend combined with increased precipitation can result in increased snow, not rain, and in growth, not shrinkage, of snow and ice cover, so long as the temperature remains below freezing [10, 27, 90, 101]. This severely complicates modeling and trend interpretation of snow and ice behavior because an increase in snow and ice could result from a cooling or a warming trend, depending on the specific prevailing temperature and precipitation conditions.

For example, hemispheric and global temperature trends, if accepted at face value, indicate a significant warming of roughly 0.2–0.3°C over the last 15 or so years [65–67]. During this same approximate time period, there has been no clear trend in monthly or seasonal average snow cover area for North America, Eurasia, and the Northern Hemisphere as a whole [136, 167] or in mean monthly sea ice area for the Antarctic or Arctic [115, 136, 168], other than the expected large seasonal and interannual variability. And alpine glacier data for 1960 through 1985 suggest a shift from a regime strongly dominated by shrinking and receding glaciers to a mixed regime, with roughly 55% of monitored glaciers advancing and 45% with positive mass balances ([165]; also see, for example, [53, 104, 112, 157]; note however that less than 1% of glaciers are monitored and that glaciers from relatively wet or maritime climatic zones are overrepresented). These snow and ice trends would appear, at first glance, to be rather inconsistent with the pronounced reported warming. But given the complex feedback processes described earlier, multiple interpretations are possible.

As indicated above, changes in cloud, snow, and ice cover can affect the global or planetary albedo, that is, the extent to which solar radiation is reflected back to space and not captured in the earth's atmosphere. The planetary albedo is a composite of numerous variables summarized in Table 1 that also include stratospheric and tropospheric aerosols (discussed earlier), ocean plankton, and land use. As indicated in Table 1, most trends seem to be either uncertain or moving in ways that would be expected to increase albedo, but the uncertainty especially about cloud cover and ocean phytoplankton makes it very difficult to estimate overall changes in albedo.

Phytoplankton (among other plankton) appears to be perhaps as complex as cloud cover, with net phytoplankton biomass a function of surface and near-surface ocean temperatures, nutrient availability, vertical ocean mixing, and surface wind stress (see e.g. [142]). Also, while shifts in land use from closed forest to open forest to grassland to cleared farmland generally increase albedo, the actual albedo is a complex function of the vegetation type and mix, vegetation cover, soil type and depth, and soil moisture, among other factors [99, 146, 159]. In addition, the combined albedo effects of multiple variables acting simultaneously (e.g. tropospheric aerosols, low cloud cover, and snow cover; or cloud cover and forest cover) are not well understood (see e.g. [116]).

UNPRECEDENTED CLIMATIC CONDITIONS

Given such a complex climate system, as reflected in the various inputs and feedbacks discussed above, researchers have looked to the paleoclimatic record as an analogous indication of future climatic change [78, 150], especially with respect to the effects of increasing concentration of atmospheric trace gases. An important caveat is that current climatic conditions appear to be unprecedented, and therefore it is not clear whether and to what extent past climate behavior serves as a valid guide to the future.

First of all, the atmospheric concentration of CO_2 appears to already exceed any level experienced over the last 160k yr and perhaps longer. CO_2 has increased from an estimated 270–280 parts per million (ppm) in the early 1800s to 315 ppm in 1958 (when C. D. Keeling began continuous direct monitoring) to about 345 ppm in 1985 [111, 135], to about 350 ppm in 1988. Paleoclimatic data place the previous peak CO_2 level at about 290–300 ppm 135k yr ago, based on chemical analysis of air bubbles trapped in ice cores and thought to be more accurate than the previously estimated 350 ppm based on carbon isotopic analysis of ocean sediments [9, 126]).

Second, the rate of increase in CO_2 concentration appears to be more than an order of magnitude faster than previously experienced. The recent build up from 275 to 350 ppm occured over about 150–200 yr compared to an estimated 6–8k yr for a roughly similar build-up (from 190–200 to 290–300 ppm) starting about 140k yr ago, prior to the last interglacial, and for a slightly smaller build-up (from 190–200 to 270–280 ppm) starting about 15k yr ago prior to the present interglacial [9, 97].

Third, several other trace gas concentrations are increasing almost as fast or faster than CO_2. Nitrous oxide is increasing almost as fast (0.2%/yr), methane at a faster rate (of roughly 1%/yr), and chlorofluorocarbons at a much faster rate (of 5%/yr) [28, 135]. Like CO_2, nitrous oxide and methane have both natural and anthropogenic sources and have increased dramatically over the last 150 years [106, 135]. Chlorofluorocarbons derive from anthropogenic sources, have no known antecedent in pre-industrial times, and in addition to greenhouse effects are thought to contribute to stratospheric ozone depletion [28, 135].

Fourth, the present interglacial is widely estimated to be about 10–11k yr old, and would be expected, on the average, to be in its late stages, and

Table 1. Factors affecting planetary albedo

Variable	Effect of increase on albedo*	Current trend in variable†
Cloud cover		
high, thin	−	Unknown
low, thick	+	Unknown
Deforestation	+	+
Desertification	+	+
Intensive agriculture (plowing, overgrazing)	+	+
Ocean phytoplankton (at sea surface)	+	Unknown
Snow and ice cover	+	Variable ±; no clear trend
Stratospheric aerosols	+	Variable ±; no clear trend
Tropospheric aerosols	±	+
Urbanization	−	+

* Effect of an increase in the variable on albedo. (+) means an increase in the variable would be expected to increase albedo, all other things being equal; (−) means an increase would be expected to decrease albedo; (±) means an increase would be expected to increase or decrease albedo, depending on the aerosol characteristics.

† (+) or (−) means data are sufficient to establish a clear trend; (unknown) means data are insufficient to establish any trend; (variable ±) means data suggest significant interannual variability but no clear trend.

Sources: cited in text plus [5, 21].

characterized by long-term cooling, since over the last 2 million yr, glacial periods of about 90–100k yr have been separated by interglacials of about 10–12k yr (see e.g. [75, 137, 150]). Numerous paleoclimatic data, while far short of global coverage, suggest that many locations around the world have indeed experienced a general cooling trend over the last several thousand years [137, 151]. Illustrative data for changes in Northern Hemisphere tree lines, zonation, and permafrost extent are summarized in Table 2. These long-term trend data are consistent with the expected effects of changes in the earth's orbit (the Milankovitch cycles) to gradually reduce incident solar radiation in the climatically sensitive high latitudes of the northern hemisphere [32, 48].

Fifth, forested areas of the world have decreased substantially over the last 200–300 yr, initially due to the advent of large-scale agriculture in the temperate zones, and more recently due to deforestation of the tropical forests and the emerging 'Waldsterben' or forest decline and death phenomenon in the temperate and boreal zones (most likely due to multiple causal factors [72, 108, 149]). The total area of global forest cover appears to be conservatively 15% smaller as of 1980 than at any time during at least the last several thousand years and possibly since the last interglacial (carbon flux analyses suggest that forest biomass may be up to 30–40% smaller [61, 166]). This is due to: (1) a slight long-term reduction in temperate-boreal forests from natural causes (see tree line and zonation references cited in Table 2) that may accelerate rapidly due to forest decline (as of 1986 an estimated 15% of Western European coniferous forest cover showed evidence of moderate to severe damage and another 23% showed slight damage [98]); (2) a significant (i.e. about 15% overall) reduction in temperate forest cover since the early 1800s due largely to conversion to agriculture that has now stabilized [61]; and (3) a roughly 15% cumulative reduction in tropical forest cover as of 1980 that is continuing at about 0.5–1.0%/yr [61, 132].

Overall, global forest cover has been reduced by a conservatively estimated 1.3 billion ha (3.2 billion acres or 4.5 million square miles) since pre-agricultural times. And the rate of global deforestation, especially in the tropics, appears to be at least an order of magnitude faster than that previously experienced due to natural causes over at least the last 10k yr and possibly the last 115k yr (interpolated from Table 2 references; [162, 166]). Carbon flux analyses suggest that 1980 rates of reforestation were small (less than 0.05%/yr) compared to deforestation [61, 166]).

To place these trends in perspective, it is important to understand that, based on paleoclimatic data, the current global temperature and global ice volume appear to be quite similar to temperature and volume at the end of the previous interglacial period about 115k yr ago [68, 87]. But the current atmospheric concentration of CO_2 (and other trace gases) is higher and increasing rapidly rather than

Table 2. Illustrative paleoclimatic data indicative of long-term Northern Hemisphere cooling

Variable	Location	Results	Reference
Tree lines	White Mountains, California, U.S.A.	7k yr ago to present 150 m lower	LaMarche [83]
	Alps (Swiss, French, Austrian)	3–6k yr ago to present 100–400 m lower	Beug [14, Fig. 4]
	Rocky Mountains Colorado, U.S.A.	6k yr ago to present generally lower	Elias [39]
	Labrador, Canada	3k yr ago to present 70 m lower	Lamb [81]
	Temperate zone mountains	6k yr ago to present 350 m lower (average)	Lamb [82, Fig. 43]
Zonation	Ontario, Canada	6k yr ago to present 150 km southward retreat of white pine	Bjorck [15]
	Gulf Coast, Alaska, U.S.A.	7k yr ago to present growth of hemlock and spruce (conifers) relative to alder (deciduous arboreal)	Peteet [107]
	South-Central Wisconsin, U.S.A.	3.5k yr ago to present shift from oak savanna to closed oak forest	Winkler *et al.* [161]
Permafrost extent	Eurasia	6k yr ago to present 100–600 km southerly movement (1000+ km in Southern Siberia)	Lamb [82, Fig. 46] Dansgaard [32, Fig. 5.8] Washburn [144, Fig. 1.1]

Sources: references noted; all trends approximate and estimated from figures where cited.

decreasing slowly, and global forest cover appears to be much smaller and decreasing much faster. This suggests an unprecedented occurrence of an extremely rapid increase in trace gases and decrease in forestation during what would in geologic terms be the late stage of an interglacial with its expected long-term cooling.

The major climate models at least implicitly assume that the prior positive relationship between CO_2 and global temperature and inverse relationship with global ice volume (see e.g. [48, 89]) will hold in the future and that relatively short-term greenhouse warming effects will dominate longer-term cooling. However, from a systems research perspective, the unprecedented nature of current conditions makes drawing valid analogies with the past much more difficult.

ABRUPT CLIMATIC CHANGE

The major climate models used to project the effects of increasing trace gases also assume that the basic relationships among climate inputs, variables, feedback loops, and outputs will remain stable over the time period of the model runs (typically 50–100 yr for a doubling of CO_2 levels). The model results suggest that climate change, while significant, would be gradual, thereby allowing time for adjustments by agricultural and natural ecosystems and by human settlement and living patterns. Indeed, the complex feedback loops built into the climate system, and not yet fully incorporated into the major climate models, may help self-regulate the climate system and provide a large measure of stability, at least within broad ranges of values for key variables. However, a variety of paleoclimatic evidence suggests that climatic change can occur much more quickly than previously thought, and that the climate system may actually reorganize itself to sustain some new set of equilibrium conditions.

The most recent isotopic analyses of ice cores [68] confirm that over the last 160k yr (interglacial and glacial periods alike), temperature change has evidenced considerable variability. The record is characterized by multiple changes in the direction of temperature movement of roughly 1–3°C (from cooling to warming or warming to cooling) that can continue for centuries to several milennia. The exact time scale of such changes is not precisely known, since the ice cores are sampled at typically 1–2m (equivalent to 100–400 yr).

Also, proxy temperatures derived from tree-ring indicators suggest a natural regional variability of ±1–2°C over the last 400–600 yr. The proxy record indicates that temperature trends can change from warming to cooling and vice versa in just a few years and that the new trend can continue easily for several decades. This pattern seems to hold at numerous locations in North America (e.g. Longmire, Washington, U.S.A. [50]; Greenville, Maine, U.S.A. [31]; Northern Quebec, Canada [105]; Central Alaska, U.S.A., and Northwest Canada [63]; and, generally [46]).

In addition, paleobotanic data based on analyses of pollens buried in ice cores, sediments, or loess suggest that climate-induced changes in vegetation patterns can take place on time scales as short as 20 yr. While changes in vegetation, including zonation and tree lines, can lag climatic change by up to a few hundred years [83], the pollen data indicate that when climatic change reaches some critical threshold, the vegetation change can occur rapidly ([162] and references in Table 2).

A final example of abrupt climatic change is the decrease in Antarctica stratospheric ozone (known as the 'ozone hole'). The phenomenon was not predicted by atmospheric chemistry models and apparently reached significant levels in less than 10 yr. One possible explanation is that the atmospheric concentration of chlorofluorocarbons, even though growing for several decades, reached some critical threshold in the late 1970s that triggered significant ozone depletion in the Antarctic spring months. To the extent that this depletion is dependent on the formation of stratospheric ice crystals and thus on low stratospheric temperatures, it is possible that increasing CO_2 could also contribute due to enhanced stratospheric cooling that is thought to accompany the tropospheric and surface warming associated with the greenhouse effect [2, 3, 28].

Various theories have been advanced as to how the climate system might shift from a warming to cooling equilibrium and vice versa on time scales much shorter than that associated with changes in the continental ice sheets and the distribution of incident solar radiation resulting from orbital cycles. One possibility is that major ocean circulation patterns reverse themselves, for example from warm North Atlantic ocean surface temperatures (that moderate the arctic air currents flowing towards Europe) to a colder North Atlantic [20]. In general, paleooceanographic research suggests that changes in upper, intermediate, and deep or bottom water formation and circulation have a key role in major climate shifts [17, 36, 43, 79]. Another possibility is that changes in snow and ice cover in certain key geographic areas, such as the Tibetan high plateau, can trigger a chain reaction in other areas due to highly leveraged or amplified effects on planetary albedo [74]. The major climate models do not at present incorporate such possible equilibrium or threshold changes in the climate system.

CLIMATE SYSTEM OUTPUTS

Much of the concern about trace-gas induced climatic change focuses on the outputs of the climate system, shown in Figure 1, several of which were discussed earlier as climate system feedbacks (e.g. clouds, snow, and sea ice). The discussion here focuses on outputs included in the common scenario of trace gas-induced greenhouse warming that projects increasing global temperature and precipitation leading, eventually, to melting of glaciers and ice sheets and rising sea level. While this scenario might seem rather straightforward to track and verify, the climate system outputs are just as complex as the rest of the climate system, and reliable monitoring and interpretation are difficult.

For example, compiling accurate global temperature data is complex, due to the many potential error factors that can distort or bias measurements. Land and ocean trend data indicate about a 0.5±0.1°C net warming over the last century, but with a 0.2–0.3°C Northern Hemisphere cooling and Southern Hemisphere plateau from about 1940 to the late 1960s, with renewed warming thereafter ([44, 65–67]; also see Hansen and Lebedeff [58]). Various hemispheric temperature compilations show relatively high correlations ([40, 51]), but these are based on the same or similar data sets and could reflect a systemic bias. The reported 0.5°C global warming falls within the range of, and therefore is not inconsistent with, model results suggesting trace gas-induced warming of 0.3–1.0°C over the last century when considering ocean thermal lag [109, 135, 154]. On the other hand, a recent analysis [8] suggests that, at least over the last few decades, a definitive CO_2-induced temperature change could not be distinguished from natural variability in temperature.

The net 0.5°C Northern Hemisphere land surface warming trend over the last century is the most often cited indicator of climatic change. However, despite efforts by [65] and others to correct for known error factors, there is still the possibility that the reported warming trend reflects, at least in part, residual urban heat island effects [69, 76, 164]. Also, there are unreconciled differences between hemispheric trends and North American trends. For example, rural and regional temperature data for many parts of the U.S. and Canada indicate a net cooling trend since about 1940 (see references in [164]; also see [33, 34]). A recent analysis by Wigley and Jones [156] concluded that the Jones *et al.* data set does reflect North American cooling but still shows a net hemispheric warming, since there is significant regional variability within the hemispheric trend (also see [64]).

Sea surface temperature data that suggest a 0.5°C warming over the last century are suspect due to changes in measurement methods and ship navigation that may introduce a warming bias [7]. Also, a recent trend analysis [102] suggests that sea surface temperatures were quite similar before 1900 and after 1940 (at least up until the last decade or so). To the limited extent available, data on regional sea surface temperature, sea subsurface temperature, sea water salinity, and sea water density indicate widely varying trends but are not suggestive of or consistent with widespread warming of the upper ocean [7].

Another output variable is tropospheric (as compared with surface) temperature. Tropospheric temperature measurements generally avoid contamination from urban heat island effects and local geography. Data from the NOAA 63-station global radiosonde network [1, 2, 58] are generally consistent with the Jones *et al.* trends. However, other tropospheric studies have produced conflicting results [40, 153]. Also, tropospheric data dates back only to the late 1950s, and, like surface measurements, are subject to changes in instrumentation, observation time, and location. The sparse tropospheric network leaves room for error. For example, the global radiosonde network indicated a 1960–1985 warming trend in the lower troposphere for the tropics (which includes two Indian stations) of 0.12°C per decade [2]. However, a separate network of 10 radiosonde stations in India indicated a 1958–1985 cooling trend in the lower troposphere of 0.6°C per decade [77]. Thus tropospheric trends could be to some extent an artifact of the particular locations sampled, although, again, differences could be attributable to regional differences within a hemispheric or global average.

Likewise, compiling accurate precipitation data on a global basis is very difficult, due in large part to lack of systematic or any coverage for much of the ocean area [6]. For the Northern Hemisphere land areas, precipitation appears to have increased over the last century in the midlatitudes but decreased in the tropical and subtropical regions [19]. While there are still questions about the methodology and error range of precipitation trends, these trends appear to be consistent with increasing cloud cover indicated where data are available (primarily North America) and in general with theoretical understanding of the greenhouse effect (increasing temperature, humidity, cloud cover, and precipitation).

With respect to glaciers and ice sheets, monitoring is extremely limited, but the data, such as they are, are not consistent with a recent global melting trend. While roughly 90% of monitored alpine glaciers had been receding for much of this century, since the 1960s, the glaciers appear to have moved into a mixed regime, as noted earlier, with a slight majority of monitored glaciers advancing and almost half with positive mass balances [165]. The Greenland ice sheet appears to be in or close to balance (neither growing or shrinking overall) and the Antarctic ice sheet may be actually growing, although, again, data are very limited [140]. Of course, while the smaller alpine glaciers could be expected to respond to climate change on a time scale of years to decades, the gross geometry of the ice sheets is generally thought to respond on the scale of centuries to millenia.

Finally, mean relative sea level is estimated to have increased about 10–15 cm over the last century. While this increase is certainly real at the observed locations, extrapolation to a global basis is problematic since most of the ocean is not measured at all. Also, paleooceanographic data indicate that sea level has been rising in the 10–20 cm per century range for the last 5k yr at various locations (e.g. Delaware, U.S.A., Northern Canada and Puget Sound, Washington, U.S.A. [16, 42, 59]). And in any event, separating the contribution to sea level rise from thermal expansion and glacial melting as opposed to isostatic rebound or plate tectonic processes (including uplift or subsidence of continental margins and ocean floors) is very difficult [7, 41, 140]. The most recent estimate of a 2–5 cm sea level rise due to thermal expansion over the last century [155] is based on the 10–15 cm global sea level rise and 0.5°C global sea surface warming estimates with all their uncertainties. The estimate of 2–7 cm sea level rise over the last century due to glacial melting is based on limited 1900–1961 glacier data [92] which did not include the recent (post 1961) apparent shift to a mixed glacial regime.

Various other supplemental indicators of climate output have been suggested, but all have similar problems of complex interpretation and limited geographic coverage. Lake levels and permafrost gradients illustrate these points. The relationship between lake levels and climate is complex. For example, the recent rise of the Great Salt Lake in Utah, U.S.A., due apparently to increased spring runoff from heavier winter snowfall and cooler and cloudier summers, has been interpreted as consistent with a trend from summer-dominant to winter-dominant precipitation [38]. Also, the recent rise of the Great Lakes (e.g. Superior, Huron, Michigan) in the Midwest U.S.A., again due apparently to heavier winter precipitation, has been interpreted as part of long-term cycles of lake level fluctuation that mark major climatic change [85]. Monitoring of a geographically representative set of lakes, for which historical and paleoclimatic data are available, would be necessary to establish lake levels as a valid supplemental indicator.

Permafrost, or perenially frozen ground, is widespread in Alaska, Northern Canada, Siberia, Western China, and Tibet [10] and locally in various other high-mountain areas throughout the world

[52]. In general, permafrost extent responds to climatic change on a time scale of decades to centuries. However, changes in the temperature profile, or thermal gradient, of permafrost would be expected to occur almost immediately in response to climatic change. Also, changes in the thickness and creep of small patches of permafrost (known as rock glaciers) would be expected to occur on a time scale of years to decades. Recent research [80] on the permafrost thermal gradient in Northern Alaska suggests a significant warming trend over the last few decades to a century, but with a more recent cooling trend over the last decade or so (possibly due to surface changes associated with drilling). Recent research [54] on a rock glacier in the Swiss Alps also suggests a warming trend as evidenced by slow thinning of the permafrost. Compiling permafrost thermal gradient and/or flow and thickness data from a geographically representative set of locations in Eurasia as well as North America, and with special care to correct for any error factors (e.g. surface disturbances, changes in snow cover), would make this a potentially valuable supplemental indicator.

THE ROLE OF SYSTEMS SCIENCE

In systems science terminology, the climate system is properly characterized as one of organized complexity ([73]; also see generally [12]). In other words, the climate system is 'rich' in having a large number of key variables and relationships. But despite or more accurately because of this complexity, the underlying long-term behavior of the climate system is not random or unorganized in the statistical sense, although short-term climate variability may have an element of randomness. Overall, the climate system shows remarkable stability under a wide range of input conditions, reflecting in part the multiple feedback loops of Fig. 1 that give the climate system a strong self-regulating capability. Clearly, if the climate system was inherently unstable, and dominated by positive rather than negative feedback loops, climate behavior would have long since moved out of control as a result of wide natural variations in solar, atmospheric, and volcanic inputs, among others, over the last several hundred thousand years.

On the other hand, the climate system today is faced with essentially unprecedented conditions for which prior behavior may not be a reliable guide. This coupled with emerging scientific theory and data that, even within normal ranges of behavior, the climate system can change direction or even shift to a new equilibrium state on a relatively short timeframe (years to decades) is enough to warrant serious attention from the systems research community.

At a fundamental level, systems science can help define and describe the climate system in terms of key variables and relationships. This could include characterization at the meta or supersystem level (e.g. including the long-term feedbacks from output to input not now shown in Fig. 1), the system level (e.g. more refined versions of Fig. 1), and the subsystem level (e.g. more detail on cloud albedo and other feedback processes). Application of concepts from cybernetic (self-regulating) systems should be especially useful. One such application, known as the Gaia hypothesis, suggests that the earth's biota interacts with the oceans, soil, and atmosphere to help regulate climate through complex feedback loops and relationships [11, 22, 25, 88]. Another application, known as the soil depletion hypothesis, suggests that CO_2 is an intermediate agent linking changes in soil mineral content and plant/forest photosynthesis with changes in cloud cover/albedo and glacial and volcanic cycles [49, 55]. Yet a third illustrative application, a geophysical feedback hypothesis, links (a) the earth's orbital cycles to (b) changes in the interior earth (core, mantle, asthenosphere, and lithosphere) to (c) shifts in rotational and gravitational stress (as evidenced by seismicity, volcanism, geomagnetic and geoidal shifts) in combination with solar insolation cycles to (d) changes in oceanic and atmospheric circulation and, ultimately, to (e) climate change on time scales of decades to millenia [96]. Further exploration and development of these and other hypotheses could benefit greatly from more intensive application of systems science [163].

In general, the first order contribution of systems science could be to identify key factors ranging across all of the disciplines that may potentially be relevant. The use of block diagrams, flow charts, and other systems science tools for understanding the relationships between supersystems, systems, and subsystems appears to be ideally suited to developing at least qualitative models of climate processes. Systems characterized by organized complexity typically involve many scientific disciplines, and that is certainly the case with climate. Systems science could be of special help in bringing together the essential core disciplines within a systems framework. This systems review identified the following core disciplines: atmospheric science, solar terrestrial physics, climatology, paleoclimatology, geophysics, geology, geography, hydrology, glaciology, volcanology, physical, chemical, and biological oceanograpy, paleooceanography, biogeochemistry, botany, zoology, ecology, soil science, forestry, and dendrochronology. There are undoubtedly others. The information flow model of fluid and biological earth processes developed by the NASA Earth Systems Science Committee [134] offers another template for identifying relevant disciplines. Major advances in understanding climate are dependent on continuing progress in the disciplinary knowledge base but also on the higher-order interdisciplinary systems integration of this knowledge [26].

A second order contribution of systems science could be to help develop new or modified theories of climate change through the application of basic systems principles. For example, the living systems [94] and ecological systems [100, 147, 148] approaches would appear to offer great potential. Also, systems science could help in reaching judgments on the developmental and computational strategies used in climate modeling. For example, for what kinds and complexities of climate models are computerized methods appropriate? What are the tradeoffs between complexity, feasibility, accuracy, validity, and cost of computerized climate models? How can various systems models be incorporated within the GCMs? And how might the CGMs be simplified in some areas so that greater complexity in other areas (e.g. cloud, snow, and ice albedo feedbacks) can be incorporated within the computational limits of current computers? How are the results of GCMs affected by changed assumptions about key feedbacks and possible equilibrium shifts?

Systems science may offer the potential to help integrate several different types and sizes of models relevant to climate. For example, concepts from systems dynamics [45] could be used to develop a global climate model that permits the coupling of GCMs with other models that capture Gaia feedback loops, biogeochemical cycles, and the like. Previous attempts at global modeling (e.g. [91, 93, 133]) excluded climate or treated climate as a constant, in large part because of the uncertainties about climate change and the difficulty in coupling climate models to other sectoral models (e.g. energy, food, water). Basic knowledge about climate change and system dynamics has advanced to the point where much improved modeling should now be possible.

A third order contribution could be to identify needs for climate monitoring. All of the climate system input, feedback, and output variables shown in Fig. 1 need systematic monitoring. This systems review identified several areas where new or improved monitoring is especially needed, including:

— rural temperature network (to minimize urban heat island effects—utilizing measurement stations at a wide variety of forest, watershed, park, and farm locations [164]);

— tropospheric temperature network (an expanded version of the existing radiosonde network);

— alpine glacier trends (advances and retreats, changes in mass balance—coordinated by the World Glacier Monitoring Service [53, 165]);

— permafrost thermal gradients and rock glacier flow rates;

— lake levels and, possibly, lake freeze-up dates [103];

— tree-ring chronologies (as a climate-sensitive indicator of changes in terrestrial biomass, carbon flux, and albedo—perhaps under the auspices of the International Project in Dendroclimatology [62]);

— ocean plankton trends (as a climate-sensitive indicator of ocean biomass, carbon flux, and albedo [25, 37, 142]).

General themes include the need for: (a) further validation of hemispheric and global trends where data are thought to be reasonably complete (e.g. temperature); (b) development of supplemental indicators to cross-check the primary trends and to better monitor the complexities of the climate system; and (c) much faster turnaround time for processing and reporting of key data. The time delay from data collection to dissemination frequently is many months to several years, which means that too often researchers are working with outdated information. While outside the scope of this paper, a combination of satellite and ground-based (*in situ*) data collection networks along with automated transmission and advanced processing and dissemination technologies are likely to be central to improved monitoring (see generally [134]). This will need to be accompanied by a vastly upgraded international translation capability so that data and analyses reported variously in, for example, English, French, German, and Russian can be widely accessible.

A fourth order contribution of systems science could be in helping to validate major climatic change, such as the current and projected global greenhouse warming. This would really be a synthesis of systems science work on the theoretical, conceptual, modeling, systems development, monitoring, and computational levels. As is evident from the previous discussion, there are numerous remaining uncertainties. And thus the need for intensive application of systems science to help reduce the uncertainties inherent in the complex climate system. A further sense of urgency comes from the report [58], if proven accurate, that the 1987 global mean temperature was the highest in hundreds of years and is approaching the peak levels of prior interglacials (about 6k and 120k yr ago).

A fifth and final contribution of systems science could be to public policy-making on climate change. While outside the scope of this paper, the public policy implications of climatic change are potentially substantial. And given the unprecedented nature of current climatic conditions, decisions may need to be made in the face of considerable uncertainty. Systems science could help in simplifying the decision problem so that it is understandable to decision-makers yet still scientifically valid in portraying uncertainties and risks (see generally [29, 84, 163]). In the broader picture, climate change appears to be a major global challenge to scientists and policy-makers alike because of the possible implications for large-scale environmental disruption and global food production (e.g. with respect to the number of frost-free growing days), among others [23, 71, 122, 137].

Acknowledgments—This article is based in part on papers presented by the author at the May 1986 annual meeting of the International Society for General Systems Research, and the August 1986 meeting of the Institute for Tertiary–Quaternary Studies, Nebraska Academy of Sciences. The author gratefully acknowledges useful suggestions and/or critiques of earlier drafts provided by R. Bryson, R. J. Charlson, J. S. Fein, H. C. Fritts, W. Haeberli, J. Hansen, S. B. Idso, T. R. Karl, R. M. Klein, G. Kukla, H. H. Lamb, J. E. Lovelock, M. R. Riches, M. E. Schlesinger, R. C. J. Somerville, G. Watson, K. E. F. Watt, R. S. Williams, F. B. Wood, Sr and several anonymous referees.

REFERENCES

1. J. K. Angell and J. Korshover, Global temperature variations in the troposphere and stratosphere, 1958–1982. *Mon. Wea. Rev.* **3** (1983), 901–921.
2. J. K. Angell, Annual and seasonal global temperature changes in the troposphere and low stratosphere, 1960–85. *Mon. Wea. Rev.* **114** (1986), 1922–1930.
3. J. K. Angell, The close relation between Antarctic total-ozone depletion and cooling of the Antarctic low stratosphere. *Geophys. Res. Lett.* **13** (1986), 1240–1243.
4. J. K. Angell and J. Korshover, Variability in United States cloudiness and its relation to El Nino. *J. Clim. appl. Meteor.* **26** (1987), 580–584.
5. W. Bach, *Our Threatened Climate: Ways of Averting the CO_2 Problem Through Rational Energy Use*. D. Reidel, Boston, MA (1984).
6. T. P. Barnett, Long-term changes in precipitation patterns. In M. C. MacCracken and F. M. Luther (eds), *Detecting the Climatic Effects of Increasing Carbon Dioxide*, pp. 149–162. U.S. Dept. of Energy, Washington, DC (1985).
7. T. P. Barnett, Long-term climate change in observed physical properties of the oceans. In M. C. MacCracken and F. M. Luther (eds), *Detecting the Climatic Effects of Increasing Carbon Dioxide*, pp. 91–107. U.S. Dept. of Energy, Washington, DC (1985).
8. T. P. Barnett and M. E. Schlesinger, Detecting changes in global climate induced by greenhouse gases. *J. geophys. Res.* **92** (1987), 14,772–14,780.
9. J. M. Barnola, D. Raynaud, Y. S. Korotkevich and C. Lorius, Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature* **329** (1987), 408–414.
10. R. G. Barry, The cryosphere and climate change. In M. C. MacCracken and F. M. Luther (eds), *Detecting the Climatic Effects of Increasing Carbon Dioxide*, pp. 109–148, U.S. Dept. of Energy, Washington, DC (1985).
11. T. S. Bates, R. J. Charlson and R. H. Gammon, Evidence for the climate role of marine biogenic sulphur. *Nature* **329** (1987), 319–321.
12. S. Beer, *Decision and Control: The Meaning of Operational Research and Management Cybernetics*. John Wiley, New York (1966).
13. L. von Bertalanffy, *General Systems Theory*. Braziller, New York (1966).
14. H. J. Beug, Vegetation history and climatic changes in Central and Southern Europe. In A. F. Harding (ed.), *Climatic Change in Later Prehistory*, pp. 85–101. Edinburgh University Press, Edinburgh (1982).
15. S. Bjorck, Deglaciation chronology and revegetation in Northwestern Ontario. *Can. J. Earth Sci.* **22** (1985), 850–871.
16. A. L. Bloom, Sea level and coastal morphology of the United States through the Late Wisconsin glacial maximum. In S. E. Porter (ed.), *Late-Quaternary Environments of the United States*, Vol. 1, *The Late Pleistocene*, pp. 215–229. Univ. of Minnesota Press, Minneapolis, MN (1983).
17. E. A. Boyle and L. Keigwin, North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperature. *Nature* **330** (1987), 35–40.
18. R. S. Bradley and P. D. Jones, Data bases for isolating the effects of the increasing carbon dioxide concentration. In M. C. MacCracken and F. M. Luther (eds), *Detecting the Climatic Effects of Increasing Carbon Dioxide*, pp. 29–53. U.S. Dept. of Energy, Washington, DC (1985).
19. R. S. Bradley, H. F. Diaz, J. K. Eischeid, P. D. Jones, P. M. Kelly and C. M. Goodess, Precipitation fluctuations over Northern Hemisphere land areas since the mid-19th century. *Science* **237** (1987), 171–175.
20. W. S. Broecker, Unpleasant surprises in the greenhouse? *Nature* **328** (1987), 123–126.
21. L. R. Brown, W. U. Chandler, C. Flavin, J. Jacobson, C. Pollack, S. Postel, L. Starke and E. C. Wolf, *State of the World* 1987. Worldwatch Institute/W. W. Norton, New York (1987).
22. S. Brown, L. Margulis, S. Ibarra and D. Siqueros, Dessiccation resistance and contamination as mechanisms of Gaia. *Biosystems* **17** (1985), 337–360.
23. A. Bryant, Analysis and planning for CO_2 reduction and climate stabilization. In *The Energy Industries in Transition* 1985–2000, Part 1, Conf. Proceedings, pp. 579–593. International Association of Energy Economists, San Francisco, CA (1984).
24. R. D. Cess and G. L. Potter, Exploratory studies of cloud radiative forcing with a general circulation model. *Tellus* **39A** (1987), 460–473.
25. R. J. Charlson, J. E. Lovelock, M. O. Andreae and S. G. Warren, Oceanic phytoplankton, atmospheric sulphur, cloud albedo, and climate. *Nature* **326** (1987), 655–661.
26. R. S. Chen, Interdisciplinary research and integration: the case of CO_2 and climate. In K. S. Chen, E. Boulding and S. H. Schneider (eds), *Social Science Research and Climate Change: An Interdisciplinary Appraisal*, pp. 230–248. D. Reidel, Boston, MA (1983).
27. B. Choudhury and G. Kukla, Impact of CO_2 on cooling of snow and water surfaces. *Nature* **280** (1979), 668–671.
28. R. J. Cicerone, Changes in stratospheric ozone. *Science* **237** (1987), 35–42.
29. W. C. Clark and R. E. Munn (eds), *Sustainable Development of the Biosphere*. Cambridge University Press, Cambridge, U.K. (1987).
30. J. A. Coakley, Jr, R. L. Bernstein and P. A. Durkee, Effect of ship-stack effluents on cloud reflectivity. *Science* **237** (1987), 1020–1022.
31. L. E. Conkey, Red spruce tree-ring widths and densities in Eastern North America as indicators of past climate. *Quat. Res.* **26** (1986), 232–243.
32. W. Dansgaard, Past climates and their relevance to the future. In H. Flohn and R. Fantechi (eds), *The Climate of Europe: Past, Present, and Future*, pp. 208–239. D. Reidel, Boston, MA (1984).
33. H. F. Diaz and R. G. Quayle, The climate of the United

States since 1985: spatial and temporal changes. *Mon. Wea. Rev.* **108** (1980), 249–266.

34. H. F. Diaz, An analysis of twentieth century climate fluctuations in Northern North America. *J. Clim. appl. Meteor.* **25** (1986), 1625–1657.
35. R. E. Dickinson, How will climate change: the climate system and modeling of future climate. In B. Bolin, B. R. Doos, J. Jager and R. A. Warrick (eds), *The Greenhouse Effect, Climatic Change, and Ecosystems*, pp. 207–270. John Wiley, New York (1986).
36. J.-C. Duplessy and N. J. Shackleton, Response of global deep-water circulation to earth's climatic change 135,000–109,000 years ago. *Nature* **316** (1985), 500–507.
37. J. Dymond and M. Lyle, Flux comparisons between sediments and sediment traps in the Eastern Tropical Pacific: implications for atmospheric CO_2 variations during the pleistccene. *Limnol. Oceanog.* **30** (1985), 699–712.
38. J. K. Eischeid, R. S. Bradley and X. Shao, Secular climatic fluctuations in the Great Salt Lake Basin. In P. A. Kay and H. F. Diaz (eds), *Problems and Prospects for Predicting Great Salt Lake Levels*, pp. 111–122. University of Utah, Salt Lake City, UT (1985).
39. S. A. Elias, Paleoenvironmental interpretations of holocene insect fossil assemblages from four high-altitude sites in the Front Range, Colorado, U.S.A. *Arctic Alpine Res.* **17** (1985), 31–48.
40. H. W. Ellsaesser, M. C. MacCracken, J. J. Walton and S. L. Grotch, Global climatic trends as revealed by the recorded data. *Rev. Geophys. Space Phys.* **24** (1986), 745–792.
41. K. O. Emery and D. G. Aubrey, Glacial rebound and relative sea levels in Europe from tide-gauge records. *Tectonophys.* **120** (1985), 239–255.
42. M. Eronen, T. Kankainen and M. Tsukada, Late holocene sea-level record in a core from the Puget Lowland, Washington. *Quat. Res.* **27** (1987), 147–159.
43. H. Flohn, A possible mechanism of abrupt climatic changes. In N.-A. Morner and W. Karlen (eds), *Climatic Changes on a Yearly to Millenial Basis*, pp. 521–531. D. Reidel, Amsterdam (1984).
44. C. K. Folland, P. E. Parker and F. E. Kates, Worldwide marine temperature fluctuations, 1856–1981. *Nature* **310** (1984), 670–673.
45. J. W. Forrester, *World Dynamics*. Wright-Allen, Cambridge, MA (1971).
46. H. G. Fritts and J. M. Lough, An estimate of average annual temperature variations for North America. *Clim. Change* **7** (1985), 203–224.
47. W. L. Gates, The physical basis of climate. In *Proc. World Climate Conference*, WMO No. 537, pp. 112–131. World Meteorological Organization, Geneva, Switzerland (1979).
48. C. Genthon, J. M. Barnola, D. Raynaud, C. Lorius, J. Jouzel, N. I. Barkov, Y. S. Korotkevich and V. M. Kotlyakov, Vostok ice core: climatic response to CO_2 and orbital forcing changes over the last climatic cycle. *Nature* **329** (1987), 414–418.
49. G. Graefe, The missing links between plant roots and colloidal soil particles. In *Problems of Constancy and Change: The Complementarity of Systems Approaches to Complexity*, Vol. II, Conf. Proceedings, pp. 441–447. International Society for General Systems Research, Budapest, Hungary (1987).
50. L. J. Graumlich and L. B. Brubaker, Reconstruction of annual temperature (1590–1979) for Longmire, Washington, derived from tree rings. *Quat. Res.* **25** (1986), 223–234.
51. S. L. Grotch, Some considerations relevant to computing average hemispheric temperature anomalies. *Mon. Wea. Rev.* **11** (1987), 1305–1317.
52. W. Haeberli, *Creep of Mountain Permafrost: Internal Structure and Flow of Alpine Rock Glaciers*. Pub. No. 77, Versuchsanstalt fur Wasserbau, Hydrologie und Glaziologie, Zurich, Switzerland (1985).
53. W. Haeberli, P. Muller, P. Alean, and H. Bosch, Glacier changes following the Little Ice Age—the international data bases. In *Glacier Fluctuations and Climatic Change*. Symposium Proceedings. D. Reidel, Amsterdam (in press).
54. W. Haeberli and W. Schmid, Aerophotogrammetrical monitoring of rock-glacier permafrost. In *Fifth International Conference on Permafrost*, proceedings. Trondheim, Norway (1988).
55. J. Hamaker and D. Weaver, The climate cycle: an extract from the Hamaker thesis on survival. In J. A. Dillon, Jr (ed.), *Mental Images, Values, and Reality*, Vol. II, Conf. Proceedings, pp. L-31–45. Society for General Systems Research, Philadelphia, PA (1986).
56. J. Hansen, A. Lacis, D. Rind, G. Russell, P. Stone, I. Rund, R. Ruedy and J. Lerner, Climate sensitivity: analysis of feedback mechanisms. In J. E. Hansen and T. Takahashi (eds), *Climate Processes and Climate Sensitivity*, *Geophys. Monogr. Ser.*, Vol. 29, pp. 130–16. Amer. Geophys. Union, Washington, DC (1984).
57. J. Hansen, G. Russell, A. Lacis, I. Fung, D. Rind and P. Stone, Climate response times: dependence on climate sensitivity and ocean mixing. *Science* **229** (1985), 857–859.
58. J. Hansen and S. Lebedeff, Global trends of measured surface air temperature. *J. geophys. Res* **92** (1987), 13345–13372.
59. P. R. Hill, P. J. Mudie, K. Moran and S. M. Blasco, A sea-level curve for the Canadian Beaufort Shelf. *Can. J. Earth Sci.* **22** (1985), 1383–1393.
60. M. I. Hoffert and B. P. Flannery, Model projections of the time-dependent response to increasing carbon dioxide. In M. C. MacCracken and F. M. Luther (eds), *The Potential Effects of Increasing Carbon Dioxide*, pp. 149–190. U.S. Dept. of Energy, Washington, DC (1985).
61. R. A. Houghton, W. H. Schlesinger, S. Brown and J. F. Richards, Carbon dioxide exchange between the atmosphere and terrestrial ecosystems. In J. R. Trabalka (ed.), *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, pp. 113–140. U.S. Dept. of Energy, Washington, DC (1985).
62. M. K. Hughes, Requirements for spatial and temporal coverage—introduction. In L. Kairiutestis, Z. Bednarz and E. Feliksik (eds), *Methods in Dendrochronology: East–West Approaches*, pp. 107–116. International Institute of Applied Systems Analysis, Polish Academy of Sciences, Warsaw (1987).
63. G. C. Jacoby, Jr, E. R. Cook and L. D. Ulan, Reconstructed summer degree days in central Asia and Northwestern Canada since 1524. *Quat. res.* **23** (1985), 18–26.
64. P. D. Jones and P. M. Kelly, The spatial and temporal characteristics of Northern Hemisphere surface air temperature variations. *J. Climatol.* **3** (1983), 243–252.
65. P. D. Jones, S. C. B. Raper, R. S. Bradley, H. F. Diaz, P. M. Kelly and T. M. L. Wigley, Northern Hemisphere surface air temperature variations, 1851–1984. *J. Clim. appl. Meteor.* **25** (1986), 161–179.
66. P. D. Jones, S. C. B. Raper and T. M. L. Wigley, Southern Hemisphere surface air temperature variations, 1851–1984. *J. Clim. appl. Meteor.* **25** (1986), 1213–1230.
67. P. D. Jones, T. M. L. Wigley and P. B. Wright, Global temperature variations, 1861–1984. *Nature* **322** (1986), 430–434.
68. J. Jouzel, C. Lorius, J. R. Petit, C. Genthon, N. I. Barkov, V. M. Kotlyakov and V. M. Petrov, Vostok ice core: a continuous isotopic temperature record over the last climatic cycle (160,000 years). *Nature* **329** (1987), 403–408.
69. T. R. Karl and R. G. Quayle, Climatic change in fact and in theory: are we collecting the facts? *State Climatologist* **11** (1987), 8–18.
70. W. W. Kellogg and S. H. Schneider, Climate stabilization: for better or worse? *Science* **186** (1974), 1163–1172.
71. W. W. Kellogg and R. Schware, Society, science, and climate change. *Foreign Affairs* **60** (1982), 1076–1109.
72. R. M. Klein and T. D. Perkins, Cascades of causes and effects of forest decline. *Ambio* **16** (1987), 86–93.
73. G. J. Klir, Complexity: some general observations. *Syst. Res.* **2** (1985), 131–140.
74. M. Kuhle, Subtropical mountain- and highland-glaciation as ice age triggers and the waning of the glacial periods in the Pleistocene. *GeoJournal* **14** (1987), 393–421.

75. G. Kukla, End of the last interglacial: predictive model of the future? In E. M. Baker, V. Zinderen and J. A. Coetzee (eds), *Paleoecology of Africa*, Vol. 12, pp. 395–408. A. A. Balkema Press, Rotterdam (1980).
76. G. Kukla, J. Gavin and T. R. Karl, Urban warming. *J. Clim. appl. Meteor.* **25** (1986), 1265–1270.
77. K. R. Kumar, L. S. Hingane and Bh. V. R. Murty, Variation of tropospheric temperature over India during 1944–85. *J. Clim. appl. Meteor.* **26** (1987), 304–314.
78. J. E. Kutzbach, Modeling of paleoclimates. *Rev. Geophys.* **28A** (1985), 159–196.
79. L. D. Labeyrie, J. C. Duplessy and P. L. Blanc, Variations in mode of formation and temperature of oceanic deep waters over the past 125,000 years. *Nature* **327** (1987), 477–482.
80. A. H. Lachenbruch and B. V. Marshall, Changing climate: geothermal evidence from permafrost in the Alaskan Arctic. *Science* **234** (1986), 689–696.
81. H. F. Lamb, Palynological evidence for postglacial change in the position of tree limit in Labrador. *Ecological Monogr.* **55** (1985), 241–258.
82. H. H. Lamb, *Climate, History, and the Modern World*. Methuen Press, London (1982).
83. V. C. LaMarche, Jr, Holocene climatic variations inferred from treeline fluctuations in the White Mountains, California. *Quat. Res.* **3** (1973), 632–660.
84. K. C. Land and S. H. Schneider, Forecasting in the social and natural sciences: an overview and analysis of isomorphisms. *Clim. Change* **11** (1987), 7–34.
85. C. E. Larsen, Geoarcheological interpretation of Great Lakes Coastal environments. In J. K. Stein and W. R. Farrand (eds), *Archeological Sediments in Context*, pp. 91–110. Center for the Study of Early Man, Inst. for Quat. Studies, Univ. of Maine, Orono (1985).
86. K.-N. Liou, S. C. S. Ou and P. J. Lu, Interactive cloud formation and climatic temperature perturbations. *J. atmos. Sci.* **42** (1985), 1969–1981.
87. C. Lorius, J. Jouzel, C. Ritz, L. Merlivat, N. I. Barkov, Y. S. Korotkevich and V. M. Kotlyakov, A 150,000-year climatic record from Antarctic Ice. *Nature* **316** (1985), 591–596.
88. J. E. Lovelock, *GAIA: A New Look at Life on Earth*. Oxford University Press, Oxford (1979).
89. S. Manabe and A. J. Broccoli, A comparison of climate model sensitivity with data from the last glacial maximum. *J. atmos. Sci.* **42** (1985), 2643–2651.
90. L. R. Mayo and D. C. Trabant, Observed and predicted effects of climatic change on Wolverine Glacier, Southern Alaska. In J. H. McBeath (ed.), *The Potential Effects of Carbon Dioxide-Induced Climatic Changes in Alaska*, pp. 114–123. University of Alaska, Fairbanks, AK (1984).
91. D. H. Meadows, D. L. Meadows, J. Randers and W. W. Behrens, *The Limits to Growth*. Universe, New York (1972).
92. M. F. Meier, Contribution of small glaciers to global sea level. *Science* **226** (1984), 1418–1421.
93. M. Mesarovic and E. Pestel, *Mankind at the Turning Point*. E. P. Dutton, New York (1974).
94. J. G. Miller, *Living Systems*. McGraw Hill, New York (1978).
95. J. G. Miller and J. L. Miller, The earth as a system. *Behav. Sci.* **27** (1982), 303–322.
96. N.-A. Morner, Planetary, solar, atmospheric, hydrospheric, and endogene processes as origin of climatic changes on the earth. In N.-A. Morner and W. Karlen (eds), *Climatic Changes on a Yearly to Millenial Basis*, pp. 483–507. D. Reidel, Amsterdam (1984).
97. A. Neftel, H. Oeschger, J. Schwander, B. Stauffer and R. Zumbrunn, Ice core sample measurements give atmospheric CO_2 content during the past 40,000 yr. *Nature* **295** (1982), 220–223.
98. S. Nilsson and P. Duinker, The extent of forest decline in Europe. *Environ.* **29** (1987), 4–9, 30–31.
99. M. Y. Nunez, W. J. Skirving and N. R. Viney, A technique for estimating regional surface albedos using geostationary satellite data. *J. Climatol.* **7** (1987), 1–11.
100. E. P. Odum, *Fundamentals of Ecology*. W. P. Saunders, Philadelphia, PA (1971).
101. J. Oerlmans, Response of the Antarctic ice sheet to a climatic warming: a model study. *J. Climatol.* **2** (1982), 1–11.
102. A. H. Oort, Y. H. Pan, R. W. Reynolds and C. F. Ropelewski, Historical trends in the surface temperature over the oceans based on the COADS. *Clim. Dynam.* **2** (1987), 29–38.
103. M. A. Palecki and R. G. Barry, Freeze-up and break-up of lakes as an index of temperature changes during the transition seasons: a case-study for Finland. *J. Clim. appl. Meteor.* **25** (1986), 893–902.
104. G. Patzelt, Glaciers of the Austrian Alps, 1984/85. *Oeav-Mitteilungen* **41** (1986), 4–8.
105. S. Payette, L. Filion, L. Gauthier and Y. Boutin, Secular climate change in old growth tree-line vegetation of Northern Quebec. *Nature* **315** (1985), 135–138.
106. G. I. Pearman, D. Etheridge, F. de Silva and P. J. Fraser, Evidence of changing concentrations of atmospheric CO_2, N_2O, and CH_4 from air bubbles in Antarctic ice. *Nature* **320** (1986), 248–250.
107. D. M. Peteet, Modern pollen rain and vegetational history of the Malaspina Glacier District, Alaska. *Quat. Res.* **25** (1986), 100–120.
108. B. Prinz, Causes of forest damage in Europe. *Environ.* **29** (1987), 11–15, 32–37.
109. V. Ramanathan, R. J. Cicerone, H. B. Singh and J. T. Kiehl, Trace gas trends and their potential role in climatic change. *J. geophys. Res.* **90** (1985), 5547–5566.
110. M. R. Rampino and S. Self, Sulphur-rich volcanic eruptions and stratospheric aerosols. *Nature* **310** (1984), 677–679.
111. D. Raynaud and J. M. Barnola, An Antarctic ice core reveals atmospheric CO_2 variations over the past few centuries. *Nature* **315** (1985), 309–311.
112. L. Reynaud, European glaciological data and their relation with climate. In A. L. Berger (ed.), *New Perspectives in Climate Modeling*, pp. 47–60. Elsevier, New York (1984).
113. A. Robock, An updated climate feedback diagram. *Bull. Am. Meteor. Soc.* **66** (1985), 786–787.
114. E. Roeckner, U. Schlese, J. Biercamp and P. Loewe, Cloud optical depth feedbacks and climate modeling. *Nature* **329** (1987), 138–140.
115. C. F. Ropelewski, Spacial and temporal variations in Antarctic Sea Ice (1973–1983). *J. Clim. appl. Meteor.* **22** (1983), 470–473.
116. W. R. Rouse, Examples of enhanced global solar radiation through multiple reflection from an ice-covered Arctic Sea. *J. Clim. appl. Meteor.* **26** (1987), 670–674.
117. R. A. Schiffer and W. B. Rossow, ISCCP global radiance data set: a new resource for climate research. *Bull. Am. Meteor. Soc.* **66** (1985), 1498–1505.
118. M. E. Schlesinger and J. F. B. Mitchell, Model projections of equilibrium climatic responses to increased CO_2 concentration. In M. C. MacCracken and F. M. Luther (eds), *The Potential Climatic Effects of Increasing Carbon Dioxide*, pp. 81–147. U.S. Dept. of Energy, Washington, DC (1985).
119. M. E. Schlesinger, W. L. Gates and Y.-J. Han, The role of the ocean in CO_2-induced climatic change: preliminary results from coupled atmosphere–ocean general circulation models. In J. C. J. Nihoul (ed.), *Coupled Ocean–Atmosphere Models*, pp. 447–478. Elsevier, Amsterdam (1985).
120. M. E. Schlesinger, Equilibrium and transient climatic warming induced by increasing atmospheric CO_2. *Clim. Dynam.* **1** (1986), 35–51.
121. M. E. Schlesinger and J. F. B. Mitchell, Climate model simulations to the equilibrium climatic response to increased carbon dioxide. *Rev. Geophys.* **25** (1987), 760–798.
122. S. H. Schneider and R. Londer, *The Coevolution of Climate and Life*. Sierra Club Books, San Francisco, CA (1984).
123. S. H. Schneider, An international program on 'global change': can it endure?—an editorial. *Clim. Change* **10** (1987), 211–218.

124. C. B. Sear, P. M. Kelly, P. D. Jones and C. M. Goodess, Global surface-temperature responses to major volcanic eruptions. *Nature* **330** (1987), 365–367.

125. W. L. Seaver and J. E. Lee, A statistical examination of sky cover changes in the contiguous United States. *J. Clim. appl. Meteor.* **26** (1987), 88–95.

126. N. J. Shackleton, M. A. Hall, J. Line and C. Shuxi, Carbon isotope data in core V19–30 confirm reduced carbon dioxide concentration in the ice age atmosphere. *Nature* **306** (1983), 319–322.

127. T. Simkin and L. Siebert, Explosive eruptions in space and time: durations, intervals, and a comparison of the world's active volcanic belts. In *Explosive Volcanism: Inception, Evolution, and Hazards*, pp. 110–121. U.S. National Research Council, Geophysics Study Committee, National Academy of Sciences Press, Washington, DC (1984).

128. R. C. J. Somerville and L. A. Remer, Cloud optical thickness feedbacks in the CO_2 climate problem. *J. geophys. Res.* **89** (1984), 9668–9672.

129. R. C. J. Somerville and S. Iacobellis, Cloud-radiation interactions: effects on cirrus optical thickness feedbacks. In *Short- and Medium-Range Numerical Weather Prediction*, Symposium Proceedings, pp. 177–185. World Meteorological Organization, Tokyo (1986).

130. O. Thiele and R. A. Schiffer (eds), *Understanding Climate: A Strategy for Climate Modeling and Predictability Research*. U.S. National Aeronautics and Space Administration, Washington, DC (1985).

131. O. B. Toon and J. B. Pollack, Atmospheric aerosols and climate. In B. J. Skinner (ed.), *Climates Past and Present*, pp. 123–133. William Kaufmann, Los Altos, CA (1981).

132. U.S. Congress, Office of Technology Assessment, *Technologies to Sustain Tropical Forest Resources*. U.S. GPO, Washington, DC (1984).

133. U.S. Council on Environmental Quality and U.S. Department of State, *The Global 2000 Report to the President: The Technical Report*—Vol. II. U.S. GPO, Washington, DC (1980).

134. U.S. National Aeronautics and Space Administration, NASA Advisory Council, Earth Systems Science Committee, *Earth System Science*. Washington, DC (1986).

135. U.S. National Aeronautics and Space Administration, *Present State of the Upper Atmosphere: Processes that Control Ozone and Other Climatically Important Trace Gases*. Washington, DC (1986).

136. U.S. National Oceanic and Atmospheric Administration, National Weather Service, Climate Analysis Center, *Climate Diagnostics Bulletin: Global Analyses and Indices*. Washington, DC (1985).

137. U.S. National Research Council, U.S. Committee for the Global Atmospheric Research Program: 1975, *Understanding Climatic Change*. National Academy of Sciences Press, Washington, DC (1975).

138. U.S. National Research Council, *Carbon Dioxide and Climate: A Second Assessment*. National Academy of Sciences Press, Washington, DC (1982).

139. U.S. National Research Council, *Changing Climate*. National Academy of Sciences Press, Washington, DC (1983).

140. U.S. National Research Council, Polar Research Board, Committee on Glaciology, *Glaciers, Ice Sheets, and Sea Level: Effects of a CO_2-Induced Climatic Change*. U.S. Dept. of Energy, Washington, DC (1985).

141. U.S. National Research Council, Committee for an International Geosphere–Biosphere Program, *Global Change in the Geosphere–Biosphere: Initial Priorities for an IGBP*. National Academy of Sciences Press, Washington, DC (1986).

142. E. L. Venrick, J. A. McGowan, D. R. Cayan and T. L. Hayward, Climate and chlorophyll a: long-term trends in the Central North Pacific Basin. *Science* **238** (1987) 70–72.

143. W.-C. Wang, D. L. Wuebbles and W. M. Washington, Potential climate effects of perturbations other than carbon dioxide. In M. C. MacCracken and F. M. Luther (eds), *The Potential Climatic Effects of Increasing Carbon Dioxide*, pp. 191–236. U.S. Dept. of Energy, Washington, DC (1985).

144. A. L. Washburn, *Periglacial Processes and Environments*. St Martin's, New York (1973).

145. W. M. Washington and G. A. Meehl, Seasonal cycle experiment on the climate sensitivity due to a doubling of CO_2 with an atmospheric general circulation model coupled to a simple mixed-layer ocean model. *J. geophys. Res.* **89** (1984), 9475–9503.

146. W. M. Washington and G. A. Meehl, General circulation model CO_2 sensitivity experiments: snow-ice albedo parameterizations and globally averaged surface air temperature. *Clim. Change* **8** (1986), 231–241.

147. K. E. F. Watt, *Principles of Environmental Science*. McGraw–Hill, New York (1973).

148. K. E. F. Watt and P. P. Craig, System stability principles. *Syst. Res.* **3** (1986), 191–201.

149. K. E. F. Watt, An alternative explanation for widespread tree mortality in Europe and North America. *Newsletter of the International Union of Societies of Foresters* **25** (1987), 8–9.

150. T. Webb, J. Kutzbach and F. A. Street-Perrott, 20,000 years of global climatic change: paleoclimatic research plan. In T. F. Malone and J. G. Roederer (eds), *Global Change*, pp. 182–219. ICSU Press, New York (1985).

151. T. Webb and T. M. L. Wigley, What past climates can indicate about a warmer world. In M. C. MacCracken and F. M. Luther (eds), *The Potential Climatic Effects of Increasing Carbon Dioxide* , pp. 237–257. U.S. Dept. of Energy, Washington, DC (1985).

152. R. T. Wetherald and S. Manabe, An investigation of cloud cover change in response to thermal forcing. *Clim. Change* **8** (1986), 5–23.

153. T. M. L. Wigley, J. K. Angell and P. D. Jones, Analysis of the temperature record. In M. C. MacCracken and F. M. Luther (eds), *Detecting the Climatic Effects of Increasing Carbon Dioxide*, pp. 54–90. U.S. Dept. of Energy, Washington, DC (1985).

154. T. M. L. Wigley and M. E. Schlesinger, Analytical solution for the effect of increasing CO_2 on global mean temperature. *Nature* **315** (1985), 649–652.

155. T. M. L. Wigley and S. C. B. Raper, Thermal expansion of sea water associated with global warming. *Nature* **330** (1987), 127–131.

156. T. M. L. Wigley and P. D. Jones, Do large-area-average temperature series have an urban warming bias? *Clim. Change* **11** (1988), in press.

157. R. S. Williams, Jr, Glacier inventories of Iceland: evaluation and use of sources of data. *Ann. Glaciol.* **8** (1986), 184–191.

158. C. A. Wilson and J. F. B. Mitchell, A doubled CO_2 climate sensitivity experiment with a global climate model including a simple ocean. *J. geophys. Res.* **92** (1987), 13315–13343.

159. M. F. Wilson, A. Henderson-Sellers, R. E. Dickinson and P. J. Kennedy, Investigation of the sensitivity of the land-surface parameterization of the NCAR community climate model in regions of tundra vegetation. *J. Climatol.* **7** (1987), 319–343.

160. R. C. Willson, H. S. Hudson, C. Frohlich and R. W. Brusa, Long-term downward trend in total solar irradiance. *Science* **234** (1986), 1114–1117.

161. M. G. Winkler, A. M. Swain and J. E. Kutzbach, Middle holocene dry period in the Northern Midwestern United States: lake levels and pollen stratigraphy. *Quat. Res.* **25** (1986), 235–250.

162. G. Woillard, Abrupt end of the last interglacial in North-East France. *Nature* **281** (1979), 558–562.

163. F. B. Wood, Sr, Philosophy of testing hypotheses and matrix of climate theories vs. evidence. In *Problems of Constancy and Change: The Complementarity of Systems Approaches to Complexity*, Vol. II, Conf. Proceedings, pp. 1240–1247. International Society for General Systems Research, Budapest, Hungary (1987).

164. F. B. Wood, Jr, Comment: on the need for validation of the Jones *et al.*, temperature trends with respect to urban warming. *Clim. Change* **11** (1988), in press.

165. F. B. Wood, Jr, Global alpine glacier trends, 1960s–1980s. *Arctic Alpine Res.* **20** (1988), in press.

166. G. M. Woodwell, J. E. Hobbie, R. A. Houghton, J. M. Melillo, O. Moore, B. J. Peterson and G. R. Shaver, Global reforestation : contribution to atmospheric carbon dioxide. *Science* **222** (1983), 1081–1086.

167. H. Yates, A. Strong, D. McGinnis and D. Tarpley, Terrestrial observations from NOAA operational satellites. *Science* **231** (1986), 463–470.

168. H. J. Zwally, C. L. Parkinson and J. C. Comiso, Variability of Antarctic sea ice and changes in carbon dioxide. *Science* **220** (1983), 1005–1012.

KEYNOTE ADDRESS: Implications of Global Climate Change

Sir Crispin Tickell KCVO
Ambassador to the United Nations
United Kingdom Mission to the United Nations
845 Third Avenue
New York, NY 10022

It is difficult for a mere ambassador to address an audience of this kind. You know a lot more about the science of the problem than I do. It would be most unwise of me to venture far into the assumptions on which this conference is based. We are here to discuss the implications of change rather than its whys and wherefores.

But to make sense of what follows I must say a word about those assumptions. We all know that the only constant in climate is its inconstancy. Our understanding of the deeper causes of change is limited and certainly incomplete. We are living in an interglacial period of relative warmth, and the return of glacial conditions during the next few thousand years seems sure. But our small scale, timebound human concerns are elsewhere. In a nutshell, the activities of our animal species in changing the chemistry of the atmosphere and the land surface of the earth could lead to a measurable increase in global surface temperatures within the next few decades, with substantial effects on life and human society.

The reasons are well known, and broadly, if not universally, accepted. The amounts of the so-called greenhouse gases in the troposphere -- especially carbon dioxide, nitrous oxide, methane, ozone, and chlorofluorocarbons -- are increasing. If current trends continue, the combination of these gases, which would be broadly equivalent to a doubling of carbon dioxide since industrial times, could cause a global mean equilibrium surface temperature increase of between 1.5 degrees and 4.5 degrees C, possibly within the next 40 to 50 years.

The regional effects of this average global increase would be varied. No model can predict them with any precision. But it seems that warming and precipitation would be greater during late autumn and winter in high latitudes than elsewhere; there would be more dryness, particularly in summer, over the continents of the northern hemisphere, particularly in middle latitudes; and there would be more convective rainfall in most tropical regions. The increase would raise sea levels by between 20 centimetres and 1.4 metres. A larger rise cannot be excluded, particularly if the West Antarctic ice shelf were to slide into the sea (as it may have done in other warmer periods), but this seems at present unlikely.

These predictions contain many uncertainties. Some are worth mentioning. We are not sure of the sensitivity of the system to changes in carbon dioxide; nor of the absorptive capacity of the oceans, and their role as an inertial stabilizer, nor of the feedback effects of cloud and ice; nor of changes in the vegetative character of the land surface; nor of the natural climatic changes which must combine with any induced by human activity.

For our species, as for other species and forms of life, the problem is not whether the world is to become cooler or warmer. Living things have adapted to colder or warmer conditions countless times in the past. Some have flourished; some have perished; most have adjusted themselves. The central problem is easily stated. It is change itself; its speed and -- closely linked with it -- the capacity of each individual species to adapt itself to a new environment.

Our species has a good record. We are among the most adaptable of all creatures, as can be seen by our presence in every territorial environment. Most of the time we are scarcely conscious of change. Indeed, we are genetically programmed to respond only to the relatively small changes which take place during the span of a human life. This makes it hard for us to understand the longer-term rhythms. The concept of 10,000 years ago, when the last ice age came to an end, can no more be grasped as a reality than that of 160,000 years ago, when the supernova in the Greater Magellan cloud blew up and began to send the light which reached us on 23 February 1987. But if an individual cannot grasp the enormity of time, how much less can a human society and the governments which run each nation within it. Few governments think more than four or five years ahead. Long-term evils can be short-term goods. Never is this more true than in looking at such problems as those of a climatic warming.

The first question a government must ask is: Can you prove it? The second is: What will happen and when? Will it be good or bad? And the last question is: What should be done about it? I deal with these questions in turn.

Can we prove it? The answer is still: "No." It can be shown that the quantity of greenhouse gases in the atmosphere is steadily increasing. It can also be shown that global mean equilibrium surface temperatures have risen since the beginning of this century, and the seas have deepened. But we cannot demonstrate the linkage between the greenhouse gas increase and the warming. There has been a search for reliable indicators. One idea was to measure the seasonal spread and melt of Antarctic sea ice. But it did not provide proof.

The next question is: What will happen and when? Will it be good or bad? Here we must reckon with the enormous complexity and multifarious character of any major change in the natural environment. First, there are the virtually unknowable chains of causation in the loops of negative and positive feedback. Some changes are self-correcting. An example is the El Nino Southern Oscillation. Other changes accentuate themselves before arriving at a different equilibrium. An example is the rapid onset or equally rapid end of a glaciation.

Second, there is the rapidly changing character of the earth's land surface. Little as we know about the interactions of oceans and atmosphere, we know less about how land use affects climate, at least on a regional scale. In the fertile temperate areas of the world, where -- it is no coincidence -- industrial development with its many penalties for the environment first took place, a broad balance has been reestablished. Still, it is a sobering thought that more than one percent of the United States is under concrete, and that spreading urbanization has created local climates of its own. Elsewhere in the world, where soils are fragile and vulnerable, the relentless pressure of human population increase with attendant domestic animals has led to destruction of forest cover and the spread of savanna-type vegetation. These have in turn accelerated soil erosion and the advance of deserts. The consequences on climate have yet to be assessed.

Would warming be good or bad? In the crude sense that some areas now arid or semiarid would get more rain and that monsoons would become more regular, the countries concerned might reckon that warming would be beneficial to them. Likewise, an enhanced concentration of carbon dioxide in the atmosphere should theoretically improve certain crop yields and thus agricultural production. Laboratory experiments suggest that, depending on growing conditions, and excluding climatic change, a doubling of the concentration of carbon dioxide would cause an increase in growth and yield of up to 10 percent in maize, sorghum, and sugarcane, and an increase of up to 50 percent in wheat, soya bean, and rice. All would depend on the combination of such factors as temperature, precipitation, radiation, and soil nutrients, and the potential benefits would vary widely from region to region. Certainly the cards of economic advantage would over time be re-dealt between countries, with interesting results.

If some were advantaged, more would be disadvantaged. Again in a crude sense, areas which now enjoy climatic benefits might find them drastically reduced. Precipitation is not a zero sum game and might on average be enhanced; but according to most forecasts, many regions including those with the most productive soils might face increasing aridity. But the biggest problem for all would be change itself.

In earlier times people could -- and did -- react to change with their feet. They just moved on to where conditions were better. But with increasing population density and resources which are exploited to the maximum, large movements of people would scarcely be possible. The more perfectly adapted a society -- like a species -- is to its particular environment, the less easy for that society -- or species -- to adapt itself. This is as true of societies with limited resources which suddenly receive a bonanza of rain as it is for societies to which rain is cut off and water becomes precious. So in our overstretched human world all change means dislocation. Time, -- the rate of change -- is the key question we are last able to answer.

Climatic problems cannot be taken in isolation. Apart from population increase, urban growth, destruction of forests, soil erosion, and the growth of deserts, there are the linked issues of mismanagement of water resources; pollution of land, sea, and air; threats to health arising from pesticides, chemicals, and pathogens; and the numerous by-products of the means by which we generate energy. These factors affect all societies, and they apply as much within countries as between them.

Then there is a related issue arising from the loss of species and genetic resources. We are used to seeing ourselves as kings of the earth, and look at natural problems in a myopically human way. But climatic change would affect the myriad interdependent networks of all living things -- animals, fish, insects, plants, funguses -- of which we are in truth so tiny a part. Age-old relationships and characteristics would be upset, and new ecosystems would emerge. The role of adapted bacteria and viruses would be important, not only for our own species, but for those other species of animal and plant on which we depend.

Perhaps the best way to bring these points home is to give an example. The clearest is the current fate of the river Nile. This great river, which has nourished civilization for more than 7,000 years, is in trouble for both natural and manmade reasons. Over three-quarters of the water which reaches the Mediterranean comes from Ethiopia. Yet Ethiopia is now in its seventh year of severe drought, and the flow of water into Lake Nasser above the Aswan Dam has fallen year by year. Reserves are now lower than in living memory and the Aswan Dam itself has proved an uncertain benefit. It has brought greater security, electricity for domestic and industrial use (around 28 percent of total Egyptian requirements), and extension of irrigation schemes.

At the same time, however, more water has evaporated, waterborne diseases have spread, and the supply of nutrient silts has been so reduced that the delta is beginning to wash away into the sea and the East Mediterranean fishing industry has been virtually ruined. The other riverine states -- Ethiopia, the Sudan, Uganda, and Kenya, all of which take water from the river -- are now talking about taking more to meet the needs of their increasing populations. Egypt itself with an annual rate of increase of 3 percent -- or one million people every eight months - has the biggest needs of all.

Now suppose that the effect of warming was to permanently reduce the rainfall which reaches the Nile. The effects on the Egyptian economy could be disastrous within less than a human generation. Egypt may be a special case. Few countries are so dependent on a single resource. But droughts across Africa, recurrent flooding in Bangladesh, and the disruptions caused by El Nino have served to show the vulnerability of many countries to what are no more than blips in the operation of the weather machine.

A rise in sea levels of between 20 centimetres and 1.4 metres would help no one. A glance at the right kind of map shows clearly enough the effect on coastlines and archipelagoes. Less obvious would be the effect on estuaries, river systems, and even underground aquifers of fresh water. Preliminary work has been done in respect to the Netherlands, the United States, Bangladesh, and Egypt. Taking the case of one of them -- again Egypt -- a rise of between 1 and 3 metres could erode up to 20 percent of the nation's arable land, affecting some 10 million people. The cost of work to protect low-lying areas worldwide, including ports and industrial plants, would be astronomical.

Still more dramatic would be the effect on the Maldive Islands in the Indian Ocean, with their population of almost 200,000 people. As the Maldives President said in the debate on the Brundtland Commission Report in the United Nations General Assembly on 19 October,

> "a mean sea level rise of 2 metres would suffice to virtually submerge the entire country of 1,190 small islands... With a mean 1 metre rise, a storm surge would be catastrophic and possibly fatal."

I turn to the last of the questions which governments must ask themselves. Faced with the prospect of a global warming, what should be done about it? Speaking now as a government servant, the most obvious requirement is for more knowledge. On the one hand governments and the international community generally must acquire an understanding on which future decisions could be taken; and on the other hand public opinion must be aware of the nature and scope of a problem which will affect the pattern of life itself.

Certain governments and their agencies, conspicuously those of the United States, the Soviet Union, Canada, and Britain, have long had research programmes of their own. For the international community we have the World Climate Programme with its four research programmes, the World Meteorological Organization, the International Council of Scientific Unions, and the United Nations Environment Programme. It sounds a lot. But most would agree that the funds devoted to national and international research are not enough.

Each of us has priorities about what research most needs to be done. I mention some obvious ones: clear identification of the signs of greenhouse-gas-induced warming, a better idea of the consequences in key areas, improved understanding of the sensitivity of different agricultural systems, and precise evaluation of the effects of a rise in sea levels.

Public awareness has a direct effect on the readiness of governments to finance research and eventually take decisions. Conferences, parliamentary and congressional hearings, symposiums, and reports in the press and on television have already had some effect. I myself was associated with the Global 2000 Report of 1979, and the discussion of climatic change among related issues at the London Economic Summit of 1984. Last year's Brundtland Report, of the World Commission on Environment and Development, had a large impact. It was debated in the United Nations General Assembly on 19 and 20 October. The participation of such speakers as Rajiv Gandhi of India and Robert Mugabe of Zimbabwe should help dispose of the vulgar illusion that concern for the environment is a luxury of the rich. Even more recently, President Reagan and Mikhail Gorbachev agreed at their Washington summit meeting to cooperate in work on how to deal with any climatic warming.

More important has been the public debate on the twin issues of acid deposition and ozone depletion. In the case of acid deposition, the dying of millions of trees and the poisoning of hundreds of lakes was clear for people to see. Enough is now known to persuade governments and industries to take steps to mitigate and reduce the problem to manageable levels.

More remarkable, because the effects are invisible, has been the reaction to the news of the depletion of the ozone layer. Ever since the discovery of seasonal ozone holes over the Antarctic by the British Antarctic Survey in 1985, concern has been intense. Again, the science is incomplete. But the role of chlorofluorocarbons is certain, and the effects of increased ultraviolet radiation equally so. Vested interests did not favour regulation, either national or international. "Let them eat cake" said an unwise Marie Antoinette. "Let them wear sunglasses and sunlotion" said an unwise member of the U.S. administration. But the result was the Montreal Agreement of last September to limit production and use of chlorofluorocarbons throughout the world. To judge from recent evidence, it will soon need to be tightened up. But it constitutes a most important precedent.

With greater knowledge and sustained by public concern, governments should be better equipped to make a difficult choice: whether to do the easy thing and let mankind -- as well as nature -- take its course, thereby permitting an experiment of formidable dimensions; or whether, as with ozone, to work towards global arrangements involving some measure of regulation. The implications of warming reach into every aspect of life. They are correspondingly difficult to grasp, let alone manage. But a step-by-step approach is possible. Here is how it might be made.

Obviously the main approach must be international, with national governments in a sustaining role. There are existing international institutions, some private, others supported by governments, which could take coordinating responsibility. The World Climate Programme was created for this very purpose. The United Nations Environment Programme did particularly well in organizing the Montreal Agreement on Ozone. Yet in this case, covering so many imponderables, I believe something else is required, at least at the beginning. If government leaders are to be persuaded to take action, then some catalyst in the form of a commission or panel of people distinguished in political as well as scientific life might be created. There are many precedents for groups of this kind. The Brandt Commission of the 1970s and the Brundtland Commission of the 1980s both had an impact which existing institutions, usually composed of experts, could never have hoped to achieve.

I see the function of such a body as threefold. First I think the members should, with the help of experts, draw up an inventory of the causes of likely warming and the corresponding remedies. Next they should draw up a code of good international behavior to act as a framework. Such a code would not be mandatory, but would amount to a reference system on which consensus could be built. Lastly they should examine the possibility of a network of agreements on the points defined in the code, which might, sooner or later, have more binding characteristics. Each stage represents an ascending order of difficulty. It would also represent progression in time so that each could reflect the needs of the problem as it -- and public awareness of it -- developed.

The remedies seem to fall into three broad categories. First, there is the better and proper use of energy. We need better conservation of energy; we need to make less use of coal and oil and more of natural gas; and we need to look into other renewable sources of energy of a kind still described as unconventional: they range from nuclear energy (especially fusion) to solar, tidal, and wind-generated energy. Second, we have to look at substitutes for such industrial chemicals as chlorofluorocarbons, and apply the right inducements and penalties to industry. Third, we have to examine the problem of land use, and the deforestation which has so contributed to atmospheric pollution. All carry wide implications; but each has its priority for other reasons too, and this should reinforce the consensus for action.

Of course the main responsibility for carrying out any plan would rest with individual governments. To them also would fall the responsibility for coping with the effects of the likely warming. Governments cannot do more than indicative planning over periods of decades and rely heavily on individuals and natural market forces. But public investment on the scale likely to be necessary, at least in some countries, has long lead times, and work on what to do, and on what to avoid, may already be desirable. Planners should look at all land uses, particularly food supplies; at the management of fresh water, whether for agricultural, industrial, or energy purposes; at the directions of industrial growth; at measures necessary to protect ports, cities, industries, and agricultural land liable to flooding; and at the effects of what could be a major redistribution of population in changing economies.

We live on a vulnerable planet. The multiplication of our own kind, and the way we have changed the land, sea, and air around us, require us to follow through the logic of what we have done and to manage the consequences. We should start before it is too late.

Strategic Planning Seminar on the Long-Term Implications of Climatic Change

Tuesday, January 5, 1988

co-sponsored by

World Resources Institute
1735 New York Avenue, NW, Suite 400
Washington, DC 20006
(202)638-6300

and

National Climate Program Office
National Oceanic and Atmospheric Administration
11400 Rockville Pike, Room 108
Rockville, MD 20852
(301)443-8646

Analysis and Perspective

WHERE ARE WE HEADED IN RESPONDING TO CLIMATE CHANGE?

By John C. Topping Jr.*

The past year has seen an enormous upsurge in public interest in the possibility that human activity is fundamentally altering our global climate. The initial focus for this concern has centered on growing evidence of depletion of the stratospheric ozone layer, which protects the earth from potentially deadly ultraviolet radiation.

In mid-September 1987, governments of most of the major producers and consumers of chlorofluorocarbons (CFCs) meeting in Montreal, Canada, signed an agreement to protect the stratospheric ozone layer by setting future limits on production and use of CFCs and other ozone-depleting substances. Yet before observers had an opportunity to bask in the euphoria surrounding the Montreal Protocol, the scientific and policy communities were shaken by news that the September 1987 measurements of ozone over Antarctica showed a precipitous drop below previous lows. At the same time, an international team of scientists, after analyzing the conditions in the Antarctic stratosphere, concluded that CFCs and related chlorine compounds were the principal cause of this seasonal depletion of Antarctic ozone.

Alarming as the Antarctic ozone loss was—a drop in springtime levels of over 50 percent from 1978 to 1987, it still seemed to represent a distant threat to humanity. This sharp ozone loss was unlikely to translate into many additional cases of skin cancer in view of the small human population of Antarctica, mostly scientists enshrouded with protective clothing. Perhaps the most serious direct threat posed by the thinning of the Antarctic ozone was to the marine food chain, but even here the scientific evidence was equivocal.

Thus, in late 1987, the conventional wisdom among experts was that the Antarctic ozone loss was a cause for deep concern because it was a surprise not predicted in any model and a possible harbinger of depletion in much more densely populated areas.

Theory Became 'A Stark Reality'

A few months later, this theoretical possibility became a stark reality when an Ozone Trends Panel of world class scientists assembled by the National Aeronautics and Space Administration concluded that there had been a significant drop in global ozone levels over the last decade. The NASA panel, after thorough examination of satellite and ground station data, concluded that average annual ozone levels in the Northern Hemisphere had fallen from 1969 to 1986 in a range from 1.7 to 3 percent, with the higher losses at the mid and high latitudes where the most populous parts of North America, Europe, and the Soviet Union are located.

The evidence that the stratospheric ozone depletion was a present reality, not a future possibility, instantaneously transformed the public debate. Soon thereafter, Du Pont, the world's largest producer of CFCs, announced its intention to phase out its production, and other CFC producers and users followed suit. Environmentalists, legislators, and the news media began to speak out vocally for an early ratification of the Montreal Protocol so that it could take effect by Jan. 1, 1989, and then a reopening of the negotiations as permitted by the protocol to provide for much sharper reductions or a total phaseout of CFCs and other ozone depleting compounds.

A One Century Half-Life

The great sense of urgency about the phaseout of CFCs and other chlorine and bromine compounds that destroy stratospheric ozone is attributable to their great persistence. The half-life of some of the most significant varieties of CFCs is about a century. Hence, if annual emissions remained constant, concentrations of chlorine in the stratosphere might be expected to triple from their present level of about 2.7 parts per billion. Moreover, it takes a decade or more for these compounds to reach the stratosphere after their release into the atmosphere. The CFCs and other stratospheric perturbants destroying today's stratospheric ozone are generally those released a decade or two ago.

In view of the proliferation since then in CFC uses, production, and emissions and the disposal of CFC products such as refrigerators and air conditioners whose coolants will eventually waft into the stratosphere, CFC concentrations in the stratosphere would rise even if all CFC production were immediately halted.

With significant ozone depletion already occurring at the current stratospheric concentration of 2.7 parts per billion of chlorine, a level far below that at which stratospheric models had predicted perceptible depletion, one can hardly assess the outer limits of potential damage to the stratosphere.

***John C. Topping Jr.** is the president of the Climate Institute, a Washington, D.C.-based international organization established to educate policy-makers and opinion leaders about the challenges to society posed by greenhouse-effect-induced global warming and stratospheric ozone depletion. A former staff director of the Office of Air and Radiation of the U.S. Environmental Protection Agency and co-author of the *Clean Air Handbook*, he is a graduate of Dartmouth College and Yale Law School.

Future Concentrations

A recent U.S. Environmental Protection Committee study by John S. Hoffman and Michael S. Gibbs, *Future Concentrations of Stratospheric Chlorine and Bromine*, Office of Air and Radiation, Washington, D.C. 20460, EPA 40011-881005, August 1988, concluded, "Very large increases in Clx [chlorines] and halon abundances would have been expected if the use and emissions of chlorine-containing compounds and halons had been allowed to increase without limit. The provisions of the Montreal Protocol will reduce the amount of the increase significantly but will not keep the levels of Clx and halons in the stratosphere from increasing. Significant additional reductions in emissions are required to keep the levels from increasing, possibly including a complete phaseout of the fully halogenated compounds and a freeze on methyl chloroform."

The study found, even assuming substantial global compliance with the reductions currently provided for under the Montreal Protocol, that chlorine and bromine concentrations in the stratosphere will rise well above current levels. By 2075, even with total global participation in the Montreal Protocol, stratospheric chlorine could triple to 8 parts per billion by volume (ppbv). Two parts per billion of this projection are attributable to methyl chloroform, a stratospheric perturbant not currently covered by the restrictions of the protocol.

Continued Growth Despite Montreal Protocol

Even if methyl chloroform emissions do not grow, Hoffman and Gibbs project that chlorine levels would be expected to rise to over 6 ppbv by 2075 even with total compliance with the Montreal Protocol. Moreover, they conclude that because of long atmospheric residence times and transport delays of chlorine compounds in reaching the stratosphere, stratospheric chlorine levels would continue to grow for about six to eight years even if emissions were totally eliminated.

In examining various scenarios for a phaseout of fully halogenated compounds—the principal stratospheric perturbants—Hoffman and Gibbs found that the earlier the phaseout is, the greater will be the prospects of restraining chlorine and bromine concentrations. The difference between a total phaseout of fully halogenated CFCs by 1990 and a 95 percent phaseout by 1998 would be an additional 0.8 ppbv peak level of chlorine in the stratosphere before concentrations would stabilize. This would also entail an additional 50 years before the stratospheric chlorine concentrations would fall to the levels likely under the slightly less stringent phaseout scenario.

Lee M. Thomas, administrator of the U.S. Environmental Protection Agency, has called for a tightening of the Montreal Protocol. In view of the fairly strong declarations of both U.S. major party presidential nominees concerning protection of the ozone layer, it is likely that Thomas' position will remain U.S. policy regardless of the outcome of the presidential election.

Laying The Basis For Negotiations

In fact, scientists are scheduled to gather at The Hague in the Netherlands this October to discuss new scientific data concerning ozone depletion, in effect laying the basis for negotiations to tighten the restrictions under the Montreal Protocol.

Meanwhile, the ratification process for the protocol appears to moving ahead in time for the agreement to become operative by Jan. 1, 1989. The protocol will become effective by that date provided that at least 11 countries have ratified the agreement, the ratifying countries represent two-thirds of global consumption of the covered compounds, and the Vienna Convention of 1985 has become effective. Having secured the necessary 20 ratifications, the Vienna Convention entered into force Sept. 22, 1988.

As of early October, 10 countries—Mexico, the United States, Norway, Canada, Sweden, New Zealand, Egypt, Uganda, the Ukraine, and Japan —had ratified the Montreal Protocol. The 11-nation requirement seemed sure to be met before year's end, but the two-thirds requirement would necessitate ratification by the European Community, a likely but not certain development during 1988.

If the Montreal Protocol becomes effective Jan. 1, 1989, its provisions designed to limit the production and consumption of certain CFCs and halons will go into effect six months later.

Beginning in mid-1989, developed countries must freeze production and consumption at 1986 levels. Covered chlorofluorocarbons—CFC 11, 12, 113, 114 and 115—must be cut to 50 percent of 1986 levels over the next 10 years while covered bromine compounds, Halon 1211, 1301 and 2402, must not exceed 1986 levels.

Developing countries as defined in Article 5 of the protocol are given a 10-year period during which they may, within certain constraints, increase production and consumption. After that 10-year period, they will become subject to similar requirements to cut production and consumption as the developed countries, except that the developing country restrictions will be based on consumption levels during 1995-1997, rather than during 1986.

With the June 1988 Toronto International Conference on the Changing Atmosphere having called for a complete phaseout of fully halogenated CFCs by 2000 and EPA Administrator Lee M. Thomas subsequently having called for a similar timetable, a significant tightening in restrictions on CFCs and halons seems quite likely within the next several years.

Even with strict further controls on ozone-depleting substances, the earth is likely to experience a further depletion of the stratospheric ozone layer as a result of rising chlorine and bromine concentrations. At a minimum, this will cause additional cases of skin cancer, eye disease, and immune system disorders. Sunscreen, UVB-blocking sunglasses, and additional protective clothing may help to mitigate damage to human health. Such mitigation measures are far less available to protect natural systems, vegetation, and fish, all of which could be vulnerable to a modest thinning of the ozone layer.

Due to a shift in the solar cycle which helps to generate stratospheric ozone, some mild resurgence of global ozone may be possible over the next couple of years. Yet this situation could reverse with a vengeance in the early 1990s when the earth returns to a solar minimum in which less ozone is being generated.

Besides slowing an ongoing deterioration of the stratospheric ozone layer, the restrictions of the Montreal Protocol appear likely to yield an additional benefit in restraining the acceleration of greenhouse warming. Chlorofluorocarbons are by far the largest factor in depletion of the ozone layer, but they are also powerful greenhouse gases. At present, CFCs are believed to contribute about a sixth of the total human contribution to greenhouse warming. Together with other significant greenhouse gases such as carbon dioxide, methane, nitrous oxide, and tropospheric ozone, CFCs have served to absorb solar radiation that might otherwise be reflected back into space. Yet the rate of emissions of CFCs has been growing much more rapidly than has been true of other greenhouse gases. In the years

Copyright © 1988 by The Bureau of National Affairs, Inc., Washington, D.C.
0149-8738/88/$0+.50

right before the signing of the Montreal Protocol, production of some significant categories of CFCs was growing 15 percent or more annually. Without the Montreal Protocol or other regulatory action, some experts expected that CFCs by the end of the first quarter of the next century could surpass carbon dioxide in annual contribution to global warming.

Besides the dual role of most significant stratospheric perturbants as greenhouse gases that ensures some emissions controls will yield a double benefit, there are other significant interconnections between stratospheric ozone depletion and greenhouse effect induced global warming. A rescrambling of the stratospheric chemistry, such as that which appears to underlie the so-called Antarctic ozone hole, could well shift weather circulation patterns and affect temperatures at the earth's surface. Researchers are just beginning to examine these effects, and it is not yet clear whether such changes will magnify or reduce global warming from enhancement of the greenhouse effect.

One link appears quite clear—the discovery of the Antarctic ozone hole and the global ozone depletion have also helped transform the public perception of the imminence of greenhouse warming. Until quite recently, scientific models tended to show the risk of stratospheric ozone depletion as one not likely to happen until the latter half of the 21st century. Yet a significant global depletion has already occurred, and the depletion may worsen considerably over the next few years. Appreciation of the ozone depletion threat and international efforts to address it have conditioned the public to think that the greenhouse effect may be a concern for current human society, not just for future generations. The summer of 1988 served to galvanize this concern into acute interest.

Summer Of 1988: A Turning Point In Public Concern

Ever since the late nineteenth century, when the Swedish scientist Svante August Arrhenius advanced the concept, the greenhouse effect has been viewed as a potential source of global warming. Arrhenius hypothesized that carbon dioxide would act to absorb some of the solar radiation that would otherwise have been reflected back into space. As carbon dioxide levels in the atmosphere rose, he postulated, the earth would gradually warm.

The first systematic tracking of global carbon dioxide levels was begun in 1958 by Charles Keeling at the Mauna Loa Observatory in Hawaii. Keeling's observations showed a steady increase in global concentrations of carbon dioxide. These levels have risen each year from about 315 parts per million by volume (ppmv) in 1958 to about 350 ppmv today. Extrapolating from ice cores and other indicators of past carbon dioxide concentrations, scientists have estimated pre-industrial levels of carbon dioxide to be about 275 ppmv. Human industrial and agricultural activity, largely fossil fuel burning and deforestation, has added about 75 ppmv since 1740 to global carbon dioxide levels, more than half of which has been since 1940. (See Gordon MacDonald, "Impact of Energy Strategies on Climate Change," in *Preparing for Climate Change*, Climate Institute, Ed., Rockville, Md., Government Institutes, Inc., 1988 at p. 213.)

There was a flurry of interest in the greenhouse effect in the 1970s, although this was sometimes eclipsed by press attention to a hypothesis of an imminent ice age by some contrary-minded scientists. In October 1983, three major studies rekindled interest in the possibility of greenhouse warming. Two of these were produced by the U.S. Environmental Protection Agency. One study by Stephen Seidel and Dale Keyes, *Can We Delay a Greenhouse Warming?* (Office of Policy and Resources Management, US EPA, Washington, D.C. 20460, 1983), projected a global warming of as much as 5 degrees centigrade by 2100. It suggested that there was such momentum in the global climate system even drastic changes in fossil fuel use would only marginally slow a global warming of about 2 degrees centigrade, although such changes could significantly affect global temperature averages by 2100. A companion EPA study, *Projecting Future Sea Level Rise* by John S. Hoffman, Dale Keyes, and James G. Titus (Washington, D.C., Government Printing Office, 1983), projected a sea level rise of between 56 and 345 centimeters by 2100, with a rise of 144 to 217 centimeters deemed most likely.

A third study, *Changing Climate*, Report of the Carbon Dioxide Assessment Committee of the National Academy of Sciences (Washington, D.C., National Academy Press, 1983), projected that a doubling of pre-industrial levels of carbon dioxide would be likely ultimately to raise global temperatures 1.5-4.5 degrees centigrade and that over the next hundred years a rise in global sea levels of 70 centimeters seemed probable.

Two years later, in the fall of 1985, a major scientific meeting at Villach, Austria, sponsored by the United Nations Environment Program, the World Meteorological Organization, and the International Council of Scientific Unions, concluded that, "in the first half of the next century, a rise in global mean temperature could occur which is greater than any in man's history." (Statement of UNEP, WMO, ICSU, October 1985, Villach Meeting, World Climate Programme, 1986).

In June 1986, American interest in the greenhouse effect was raised by two days of hearings by the U.S. Senate Committee on Environment and Public Works. Chaired by Senator John Chafee of Rhode Island, these hearings elicited testimony from many expert witnesses that climate change could cause the United States to lose most of its coastal wetlands and recreational beaches by 2100, would place significant stresses on agriculture, and would dramatically increase the number of days above 100 degrees Fahrenheit in many American cities. Dr. James Hansen, director of NASA's Goddard Institute for Space Studies, testified that there was a reasonable possibility that the earth could warm as much as 5 degrees centigrade by the mid-21st century.

Only a few weeks later, three British scientists—after reviewing global temperature records from 1850 through 1984—concluded that five of the nine warmest years during the 134-year period had occurred since 1978. (P.D. Jones, T.M.L. Wigley, and P.B. Wright, "Global temperature variations between 1861 and 1984," *Nature*, Vol. 322, 31 July 1986.)

Public focus on climate issues during 1987 centered largely on stratospheric ozone depletion because of concern over the Antarctic ozone hole and interest in UNEP negotiations to restrict CFCs and halons. Yet in late October 1987, barely five weeks after the signing of the Montreal Protocol, 300 scientists, corporate and governmental officials, and environmentalists assembled in Washington, D.C., for the First North American Conference on Preparing for Climate Change. Drawing together some of the top climate experts from Canada, the Netherlands, the Soviet Union, and the United States, the conference provided an unprecedented array of presentations of likely impacts of climate change on Canada and the United States. A highlight of the conference was the recommendation by Senator Chafee in the presence of the Soviet scientists that climate change be placed on the agenda of the upcoming Reagan-Gorbachev Summit.

That is exactly what happened six weeks later when the Soviet general secretary and the American president met in Washington, D.C. The summit communique stated that "the two leaders approved a bilateral initiative to pursue joint studies in global climate and environmental changes through cooperation in areas of mutual concern such as protection and conservation of stratospheric ozone, and through increased data exchanges...In this context, there will be a detailed study on the climate of the future."

Climate change was also an element in the discussions in the spring 1988 Reagan-Gorbachev Summit in Moscow. U.S. efforts under the bilateral agreement are being coordinated by Dr. Alan Hecht, director of the U.S. National Climate Program Office, while Dr. Mikhail Budyko, of the State Hydrologic Institute in Leningrad, coordinates the Soviet activity.

The growing interest of international leaders in climate change as 1988 opened was followed by some events which eventually made the greenhouse effect and climate change a matter of everyday concern in many parts of the world:

- An article by two NASA scientists, Dr. James Hansen and Dr. Sergej Lebedeff, both from the Goddard Institute for Space Studies, indicating that, based on an extensive review of global meteorological records, the four warmest years since the 1880s—1980, 1981, 1983 and 1987—all occurred in the present decade. This article in the April 1988 issue of *Geophysical Research Letters* circulated widely among the news media and served to spur press interest in climate change.
- A severe spring and summer drought in the major grain-producing areas of the United States and Canada coupled with record high summer temperatures in many of these areas.
- Unusually warm temperatures across much of the world in the first five months of 1988, well above the trend of 1980, 1981, 1983 or 1987, the four warmest since the 1880s. Unusually warm weather was experienced in China, North America, the Soviet Union, and other portions of the globe. Coming in the wake of the strong warming trend of the last 30 years, this led Dr. James Hansen to testify on June 23 "with about 99 percent confidence" that the temperature rise in the last 30 years represents a real warming trend, not a chance occurrence.
- Unusually bad air quality during the summer of 1988 in many of the major metropolitan areas of the United States as the combination of extraordinary summer heat and stagnant air fronts combined to produce high levels of tropospheric ozone.
- An outbreak of severe forest fires across much of the Western United States in consequence of prolonged drought and a severely hot summer. The most spectacular of these fires devastated much of the Yellowstone National Park.
- Devastating floods in Bangladesh that left a quarter of that nation's population homeless. The unusual severity of these floods appears to have been the result of the razing of the upland Indian and Nepalese forests that once retained much of the monsoon waters.
- Hurricane Gilbert, the most severe hurricane ever recorded in the Western Hemisphere. It wreaked havoc throughout the Caribbean region, causing an estimated eight billion dollars damage in Jamaica, and producing great damage to the resort areas of Mexico's Yucatan Peninsula and considerable loss of life in northern Mexico. Dr. Kerry Emmanuel, a meteorologist at the Massachusetts Institute of Technology, has projected that a moderate rise in sea surface temperature may increase the frequency and severity of these hurricanes.

Whether any of these developments can be attributed clearly to greenhouse warming, each underscores the vulnerability of our society to climatic events. Moreover, the climate models and impact analyses suggest that such events—heat waves, summer droughts in the North American breadbasket, a deterioration of summer air quality, forest fires, flooding in monsoon lands, and an increase in hurricane and typhoon frequency and intensity—are likely to occur more frequently as the earth warms.

International Efforts: Who Are The Players?

The upsurge of interest in addressing the greenhouse effect has been reflected in an unusual ferment of activity. On the governmental and intergovernmental side, the major players appear to be:

The United Nations Environment Program: Under the skillful leadership of its Egyptian executive director, Dr. Mostafa Tolba, UNEP managed to engineer the most comprehensive international environmental agreement ever signed, the Montreal Protocol. Despite the limitations of his annual budget of less than $40 million, Tolba is mounting an aggressive program to have UNEP play a role on the greenhouse effect much like the one it staked out for stratospheric ozone protection.

The United States Government: Most of the world's total resources devoted to research and policy analysis on stratospheric ozone depletion and the greenhouse effect are provided by the U.S. government. During fiscal year 1988, which ended September 30, 1988, the United States was spending almost $200 million on climate activities, according to data maintained by the U.S. National Climate Program. Perhaps reflecting heightened presidential interest in the issue, the Reagan administration has asked Congress for $232 million in fiscal year 1989 funds for climate activities.

While the U.S. climate activities are dispersed among about 9 different agencies, the U.S. Environmental Protection Agency appears to be in the driver's seat in developing climate policy. EPA's Office of Air and Radiation has the lead in developing regulations and international initiatives to protect the stratospheric ozone layer. EPA's Office of Policy Analysis masterminds the U.S. government effort to respond to the greenhouse effect. It is currently preparing two reports to Congress. The first of these, *The Effects Report*, is expected to be released sometime this year. This report, the result of two years of research and analysis into likely climate impacts on various sectors and regions of the United States, is certain to be the most detailed climate impact analysis ever assembled. The second report, *The Stabilization Report*, will not be complete until early in 1989. This report is likely to be of global interest as EPA's mandate from Congress was to identify strategies to stabilize concentrations in the atmosphere of greenhouse gases and identify the costs and technical feasibility of such strategies.

The Canadian Government: The first country to develop a comprehensive climate impact program, Canada is seeking to play a prominent role in developing international responses to the greenhouse effect. In hosting the very successful June 1988 Toronto International Conference on the Changing Atmosphere, Prime Minister Brian Mulroney established the priority Canada places on global and transboundary air pollution issues. The Toronto Conference Director, Howard Ferguson, a highly respected career civil servant who heads Canada's Atmospheric Environment Service, is directing Canada's global climate efforts.

The Norwegian Government: Having chaired the World Commission on Environment and Development, Norwegian

Copyright © 1988 by The Bureau of National Affairs, Inc., Washington, D.C.
0149-8738/88/$0+ 50

Prime Minister Gro Harlem Brundtland is the governmental leader most familiar with international environmental issues. She keynoted the Toronto Conference on the Changing Atmosphere this June and a couple of weeks later hosted a two-day meeting in Oslo for the U.N. secretary general and the heads of 22 U.N. organizations to explore ways that U.N. development strategies can show greater respect for environmental concerns.

The West German Government: The Federal Republic of Germany (FRG) has become a significant source of funding of basic research on climatological issues. The FRG is hosting a World Conference on Climate and Development, Nov. 7-10, 1988, in Hamburg.

Several other governments are likely to play a large role in developing responses to the greenhouse effect. Among the most prominent countries that are likely to do so are the governments of the Netherlands, Japan, and the Soviet Union.

With much of its land below sea level and sustained only by an elaborate network of dikes, the Netherlands has a vital stake in restraining the pace of global warming as well as considerable coastal engineering expertise to impart to others. The Dutch government is reportedly planning to host a fall 1989 meeting for senior environmental officials from around the world to discuss responses to the greenhouse effect. Japan, with a huge coastline, will be greatly affected by climate change and sea level rise.

Japan's Ministry for International Trade and Investment has been aggressively looking at implications of climate change for the Japanese economy. Already there are indications that Japanese companies soon may take the lead in the search for CFC substitutes and energy-saving technologies.

The Soviet government is a significant funding source for basic climatological research, and the Soviets are working closely with the United States to study the role of natural emissions from the Arctic in global warming. The Soviet government has been less active on the climate policy front due possibly to a split among Soviet climatologists over the implications of global warming for the Soviet Union. Some senior climatologists appear to view global warming to be in the long-term interest of the U.S.S.R. whose cold regions might become more habitable. A number of younger climatologists, in tune with the U.S.S.R.'s growing environmental movement, warn that rapid climate change could prove traumatic for the fragile Soviet agricultural systems as well as for natural ecosystems. To date, General Secretary Gorbachev seems to lean toward the position of the younger Soviet climatologists.

The climate policy debate is also heavily shaped by the work of atmospheric scientists, climate impact scientists, as well as climate modelers who develop detailed mathematical models that project future climate scenarios. Hundreds of universities, research firms, and government laboratories are involved in climatology research and climate impact analysis.

Only a handful of climate modeling centers exist due to the great computer capability and depth of interdisciplinary skills required. Among the most significant of such organizations are the following: the National Center for Atmospheric Research (NCAR), in Boulder, Colorado; NASA's Goddard Institute for Space Studies (GISS) in New York City; the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration at Princeton, New Jersey; Oregon State University at Corvallis, Oregon, and the Climate Research Unit at the University of East Anglia in Norwich, England.

Another group of participants in the emerging climate policy discussion are several non-governmental organizations addressing climate change. They include:

Beijer Institute, Royal Swedish Academy of Sciences, P.O. Box 5005, S-104 05 Stockholm, Sweden. The Beijer Institute in April 1988 issued a report, *Developing Policies for Responding to Climate Change*, summarizing discussions and workshops held in Villach, Austria, and Bellagio, Italy, in the fall of 1987. This document contains the most detailed presentation yet compiled of likely regional effects of climate change outside North America.

Climate Institute, 316 Pennsylvania Avenue, S.E., Suite 403, Washington, D.C. 20003, telephone (202) 547-0104. Established in 1986 to educate policy-makers, planners, and opinion leaders about the challenges posed by greenhouse warming and stratospheric ozone depletion, the Climate Institute has become the leading membership organization addressing climate issues. Its board, chaired by Dr. Stephen Leatherman, director of the University of Maryland's Laboratory for Coastal Research, includes such distinguished scientists as Dr. Stephen Schneider of NCAR, Dr. Martin Parry of the University of Birmingham, UK, and Jim McCulloch, recently retired director general of the Canadian Climate Centre. Board members also include senior executives of major corporations, Paul Pritchard, president of the National Parks and Conservation Association, and Sir Crispin Tickell, ambassador from the United Kingdom to the United Nations. Set up as a bridge institution between climate scholars and users of climate impact information, the institute has held conferences and symposia on the implications of climate change for North America, for fisheries, wildlife, infrastructure planning, and private sector investment. It is convening in Washington, D.C., Dec. 6-8, 1988, the Second North American Conference on Preparing for Climate Change. Having held two symposia in 1988 on climate change implications for Third World nations in which diplomats from over 50 countries participated, the institute has made Third World climate change impacts a top priority. The institute sends its quarterly newsletter, *Climate Alert*, to about 12,000 decision-makers and climate specialists around the world.

International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361, Laxenburg, Austria. One of the world's leading centers for interdisciplinary policy analysis concerning global climate change, IIASA has been a source of numerous highly regarded studies on likely implications of climate change. A recent IIASA two-volume study, *The Impact of Climate Variations on Agriculture*, Martin L. Parry et al., editors, IIASA and UNEP, 1988, is widely regarded as the leading work on the subject.

Resources for the Future (RFF), 1616 P Street, N.W., Washington, D.C. 20036; telephone (202) 328-5000. RFF's Climate Resources Program, headed by Dr. Norman Rosenberg, a leading expert on drought planning, has focused heavily on agriculture, natural systems, and forestry issues. Reflecting RFF's strong economist base, the Climate Resource Program has employed cost-benefit analysis to assess the feasibility of potential response strategies to address climate change.

Woods Hole Research Center, P.O. Box 296, Woods Hole, Mass. 02543; telephone (508) 540-9900. Headed by Dr. George Woodwell, widely regarded as the world's leading expert on the biotic implications of climate change, the center has focused heavily on means of slowing tropical deforestation. Woodwell was the leading scientist to warn of the threat of tropical deforestation to global and regional climates and of the threats to biological diversity posed by both deforestation and climate change. The Massachusetts center has been instrumental in organizing a meeting on implications of climate change for South Asia to be held Feb. 21-23, 1989, in Delhi, India.

World Resources Institute (WRI), 1735 New York Avenue, N.W., Washington, D.C. 20006; telephone (202) 638-6300. Founded in 1982 with the support of the MacArthur Foundation to perform research and analysis on world environmental issues, WRI has devoted much of its efforts to policy studies concerning stratospheric ozone depletion, the greenhouse effect, tropical deforestation and energy conservation. Its president, J. Gustave Speth, was chairman of the Council on Environmental Quality during the Carter administration.

Worldwatch Institute, 1776 Massachusetts Avenue, N.W., Washington, D.C. 20036; telephone (202) 452-1999. Headed by Dr. Lester Brown, this group has produced many studies on energy conservation, alternative fuels, population issues, and natural resource use. Its highly regarded publication, *State of the World*, has begun to give global climate issues considerable prominence.

While Friends of the Earth is implementing an aggressive worldwide campaign to accelerate the phaseout of stratospheric perturbants, no counterpart program exists within the traditional environmental organizations to address greenhouse warming. Instead, senior officials within these organizations have tended to act on specialized issues. They include: at the Environmental Defense Fund, Dr. Michael Oppenheimer, telephone (212) 505-2100 (air quality implications, interactive pollution effects, effects on ecosystems), and Dr. Daniel Dudek, telephone (212) 505-2100 (implications for agriculture); at the World Wildlife Fund, Dr. Robert Peters, telephone (202) 293-4800 (implications for wildlife and biological diversity), who organized a highly successful conference Oct. 4-6, 1988, at the National Zoo in Washington, D.C., on Consequences of the Greenhouse Effect for Biological Diversity; at the Conservation Foundation, Ambassador Richard Benedick, telephone (202) 293-4800 (international negotiations to protect the global climate); at the National Audubon Society, Dr. J.P. Myers, telephone (212) 546-9248 (implications for birds and wildlife refuges); and at the Natural Resource Defense Council Inc., Lynne Edgerton, Esq., telephone (212) 351-4374 (coastal protection policy) and David Wirth, Esq., telephone (202) 783-7800 (practices of international lending institutions).

The work of two scientists who are pre-eminent in the climate impacts field, Dr. Peter Gleick and Dr. Stephen Leatherman, has helped shape the policy debate. Gleick, who is based at the Pacific Institute for Studies in Development, Environment and Security (2718 Telegraph Avenue, Suite 102, Berkeley, Calif. 94705; telephone (415) 843-9550), has done ground-breaking studies on the strategic and human implications of climate-change-caused stresses on water resources in California, the Colorado River Basin, and the Nile River Basin. Leatherman's Laboratory for Coastal Research (1113 Lefrak Hall, University of Maryland, College Park, Md. 20742, telephone (301) 454-5167), is generally regarded as the leading center for analysis of coastal implications of sea level rise.

What Strategic Directions Can Be Anticipated?

Aside from the rapid thrust to phase out CFCs, also a greenhouse gas, discussions on greenhouse gases are still largely in the consciousness-raising stage. If a global consensus is to be secured for the fundamental societal changes necessary to hold greenhouse warming within tolerable bounds, world decision-makers and opinion leaders will have to become aware of the potential stakes.

This is especially critical in the Third World, source of only a modest portion of anthropogenic emissions to date but, because of expected population growth and economic development, a likely source of most greenhouse emissions by the second half of the 21st century. Energy policies adopted in the Third World countries over the next few years may greatly affect the future global climate. Moreover, at least 40,000 square miles of tropical forests are being destroyed each year and, despite the increased public focus on this issue, the rate of loss appears to be accelerating. Besides the tremendous cost of such deforestation to biological diversity and the potentially disastrous implications for regional climate—as manifested in the 1988 Bangladesh floods—this deforestation will also accelerate global warming and sea level rise.

If global action is to occur to protect the earth's atmosphere, people must begin first to think locally. When opinion leaders in Brazil recognize that the rapid erosion of the beaches of Rio de Janeiro is accelerated by large-scale burning in the Amazon, they are likely to act in their national interest, thereby safeguarding the global climate. Likewise, recognition by Indonesian leaders of the vulnerability to inundation of coastal areas of Java could increase their stake in preserving the tropical forests of Borneo. Recognition of the vulnerability of the Ganges-Brahmaputra Delta to coastal flooding could be pivotal in causing the Indian Government to choose a low greenhouse gas energy strategy.

Yet climate change impact analyses are quite sparse, although UNEP is acting aggressively to fill this gap. Once a critical mass of credible data is available, regional conferences that will attract Third World decision-makers and planners can be critical in building climate change considerations into national policy-making. A Conference on the Implications of Climate Change for Africa is being convened at Howard University in Washington, D.C., May 2-3, 1989, by the Climate Institute and UNEP. Recognizing the vulnerability of the Nile to climate change, the Climate Institute is planning a World Conference on Preparing for Climate Change to be held in Cairo, Egypt, tentatively in December 1989.

Yet, if Third World nations are to adopt low greenhouse gas development policies, it is essential that these policies not impair their prospects for economic development. Greenhouse gas emissions will affect the global climate irrespective of their country of origin. Hence, it is in the interest of industrialized countries to encourage economically attractive, low-greenhouse technologies and means of energy conservation that are readily usable in Third World countries. This realization was reflected in the recommendation of the Toronto Conference for a World Atmosphere Fund to support such technology research and transfer.

Although long-term policies to constrain growth of greenhouse emissions will require technological and institutional breakthroughs to benefit the Third World, near-term constraints on greenhouse emissions must be concentrated on the industrialized nations, the source of most current emissions. Actions by the industrialized countries can have a tangible effect on current emissions. Moreover, they will set an example that may make a more credible case for Third World countries also acting to restrain growth of greenhouse gas emissions.

The first element of any strategy would seem to be to avoid precipitous action that would compound the greenhouse gas problem. The public referendum this fall in Massachusetts to close down all nuclear plants and similar grass roots activity in Europe and Japan would, if successful,

Copyright © 1988 by The Bureau of National Affairs, Inc., Washington, D.C.
0149-8738/88/$0+.50

almost certainly result in a growth of greenhouse gas emissions. There may be legitimate reasons to be cautious about heavy reliance on nuclear power, but an ideological decision to throw out safely functioning plants without consideration of the likely substitutions can only further imperil the global environment.

A major element in any near-term strategy should be energy conservation. Utility regulatory administrators could facilitate this conservation by allowing utilities to build conservation expenditures into their rate base, and legislative bodies might provide tax incentives for such investments by homeowners.

Automobiles and trucks are a major source of greenhouse gas emissions. Increased fuel efficiency would yield commensurate reductions in carbon dioxide emissions. Moreover, the installation worldwide of already proven auto emission controls could slow the buildup of tropospheric ozone, a significant greenhouse gas, and carbon monoxide which serves to increase concentrations in the atmosphere of methane, a powerful greenhouse gas. The statement of the non-governmental organizations, i.e., environmental groups, at the Toronto Conference called for installation of catalytic converters or equivalent technology on all cars produced on earth. Such a requirement, probably one of the most cost effective of all climate protection options, is likely ultimately to be an element of a Greenhouse Gas Convention.

Although conservation, which includes increased efficiency in fossil fuel power generation, is likely to play the largest role in the next decade in constraining greenhouse emissions, energy strategies in the early part of the 21st century may make much greater use of non-carbon based energy systems. Recent breakthroughs in photovoltaic solar technology may augur well for the competitiveness of solar power within a decade. Indonesia has agreed to buy energy from four 100-megawatt ocean thermal power plants, the first to be ready during the early 1990s. If successful, this power form could proliferate in the tropical ocean countries.

Smaller scale and meltdown-proof nuclear reactors could provide another energy source which will generate almost no greenhouse emissions. There is even an outside possibility that a miniaturized form of nuclear fusion could be commercialized within this timeframe.

Breakthroughs in photovoltaic solar technology could also help to make hydrogen technology more economic. Such hydrogen generation could also produce sizable reductions in greenhouse gases.

There is likely to be no single "right" energy technology. Efforts to cope with the greenhouse gas crisis must not seek to prejudge the energy future, but instead to encourage a number of technologies.

Important as the effort to control emissions is, it would be folly to ignore adaptation measures. Even with stringent emission controls well past those which appear attainable during this century, global temperatures seem certain to rise to a level higher than the human species has ever experienced.

Legal mechanisms should be developed before the imminence of a drought to provide for short-term water sharing within regions of a country and across international boundaries. Similarly, international technical cooperation in coastal engineering and emergency management could help to mitigate the dual threat posed by likely sea level rise and increased frequency and ferocity of hurricanes and typhoons.

Development of drought-resistant seed strains and agricultural practices for a drier summer climate could allow farmers to adjust to the possibility of such change. Research should also look toward applications in Third World agriculture, where changes in climate could become a life-and-death issue for millions.

A Greenhouse Gas Convention need not start with emission controls. Instead, by developing agreements for cooperation on adaptation measures and for funding of technology transfer efforts to restrain emissions, a bond of trust could be created which would allow the negotiation of realistic constraints on global greenhouse emissions.

IMPACTS OF GLOBAL CLIMATE CHANGE ON AGRICULTURE

(By Jasper Womach, Specialist in Agricultural Policy, Congressional Research Service)

There is little dispute among scientists that the atmospheric concentrations of greenhouse gases are rapidly increasing. A number of climatologists, based on less than perfect modeling efforts, hypothesize that this will lead to general global warming but are less certain about how much warming and how rapidly (i.e., a doubling of concentrations of greenhouse gases (CO_2 and several others) might raise average global temperatures 5 to 10 degrees Fahrenheit by the middle of the 21st Century). If there is a substantial climate change, weather patterns are expected to change and the impacts on agriculture could be dramatic.

Agriculture is subject to dramatic change precisely because it is extremely sensitive to climate and weather conditions. Temperature, precipitation, growing season, and soil moisture directly affect crop yields, with small deviations from normal having sizable impacts. Also subject to climate and weather are plant pathogens and weeds, which affect crop yields. Likewise, but to a lesser degree, livestock production is both directly and indirectly affected by climate and weather.

An emerging consensus of analytical investigations concludes that global warming will not be uniform. The tropics will likely show the least warming; the mid-latitudes might be warmer and drier; and the higher latitudes might be warmer and wetter. Though the results should not be viewed as forecasts, "state-of-the-art" climate models give an indication of how regions might be differentially impacted. For example, several analyses show a shift in North American grain production from the United States toward Canada.

Though there is little certainty about how, when, or even if climate will change in the United States, there are Federal policy directions and program actions that appear appropriate for the present as well as for an uncertain future. Some of these are:

> Efforts are already being made to improve the efficiency of water use in irrigation. Water conservation research and technology could prove even more important with a warmer and drier climate.
>
> The development of drought-resistant crop varieties could help in efforts to conserve water and also preserve otherwise unsuitable lands for agriculture.
>
> Incentives and institutional mechanisms may be increasingly needed to remove arid lands from cultivation and to establish permanent cover to prevent wind erosion.
>
> Both scientific and institutional support could help farmers shift to more suitable crops and livestock if climate change alters the economics of current production practices. Institutions that now create rigidities in land use, crop selection, and other resource allocation and production management decisions may need to be modified to facilitate adjustment (i.e., commodity price supports and crop acreage bases).

If weather variations become more extreme, as some climatologists believe could happen, it may be advisable to reassess how the risks and costs of a less stable production and supply situation are shared (i.e., disaster assistance, crop insurance, reserve stocks).

The sizable and critical role that science has played in the past growth of agricultural productivity may be small compared to what could be needed in the future. It may be desirable to reexamine funding levels, which have been gradually declining when measured in inflation-adjusted dollars, and program priorities for agricultural research. Genetics and other biotechnical sciences could play critical roles in assuring adequate food supplies and an internationally competitive U.S. farm economy.

The following selections from the literature on climate change and agriculture are intended as representative rather than definitive works. Clearly the study of climate change and its agricultural impact is in its infancy. At this stage, uncertainties abound. However, the scientists appear convinced that agriculture in the United States and globally will change. At this time the consensus advice from scientific observers to agricultural policy makers is: maintain a dynamic and flexible agricultural sector, able and prepared to make changes in what is produced, how it is produced, and where it is produced.

The five reports on climate and agriculture reproduced here are arranged in succession from the general to the more specific. They treat effects such as biophysical impacts (how will yields be affected and what cropping patterns will be suitable under expected climatic changes) and the production and marketing adjustments that could possibly be necessary at national and regional levels.

The agriculture chapter in "The Potential Effects of Global Climate Change on the United States," a comprehensive study by the Environmental Protection Agency, presents a broadly focused examination of how U.S. agriculture might be affected, including policy implications to facilitate adjustment. The broad scope of the problem is demonstrated by including assessments of such important but typically neglected aspects as agricultural pest problems and environmental consequences of likely adjustments.

Just how sensitive agriculture is to weather and climate, and consequently how susceptible food supplies are to climatic change, is explained by Rosenberg in "Global Climate Change Holds Problems and Uncertainties for Agriculture." Agricultural science has enabled crops and livestock to expand their range of production into previously prohibitive weather zones. These past adaptations to unfavorable weather likely show the kinds of adjustments that will be needed as climates change. While the uncertainties of climate change may be too great to recommend specific changes in U.S. agriculture, this report highlights the importance of beginning now to identify its vulnerabilities, the likely impacts of climate change, and the technological and institutional options needed to cope with change.

In "Implication of a Global Climatic Warming for Agriculture: A Review and Appraisal," authors Smit, Ludlow, and Brklacich have prepared a well categorized survey and summary of the literature. A valuable aspect of this report, especially for readers who are not themselves scientists, is the brief and understandable review of crop yield and spatial shift analyses. A number of complex regression and simulation models, as well as surveys of expert opinion, show a consensus of current scientific thought indicating possibly dramatic decreases in yields for major grain crops now grown in some of the most productive regions of the world, including the midwestern United States.

"Assessing the Implications of Changes in Carbon Dioxide Concentrations and Climate for Agriculture in the United States," by Dudek, presents a narrowly focused examination of U.S. agriculture as it might look under conditions of increased CO_2, higher temperatures, and increased evapotranspiration rates. Dudek finds that crop production increases when only the CO_2 fertilization effect is considered but that this effect can be more than offset by some of the effects of changes in temperature extremes, moisture availability, and other factors. Using estimates of these variables derived from one model of how climate change will affect agricultural variables in the United States, he calculates yield impacts, which are analyzed in an economic model to determine equilibrium production and price adjustments. The consequences show up as regional acreage changes and changes in irrigation water use. The author stresses that this is not a forecast but is an analysis of what would happen given certain assumptions. The study leads to identification of policy issues likely to arise concerning water allocation rules and the effect of Federal agricultural commodity programs on land use.

"Strategies for Adapting Agriculture to Adapt to Climate Change," by Rawlins, proposes shifting away from the now small number of weather-vulnerable annual crop species that supply most of the food system to perennial species. This system would rely on perennial plants to supply simple sugars, using biotechnical or chemical conversion of lignocellulose. The simple sugars would then be converted to food or animal feed components. The food components and livestock would then be converted to edible products. The ability of perennials to flourish in extreme climates would make agriculture relative independent of climate. There would also be environmental benefits including reduced soil erosion, less chemical dependency, and less use of fossil fuels.

THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES

DRAFT

REPORT TO CONGRESS

Volume 2: National Studies

Editors: Joel B. Smith and Dennis A. Tirpak

United States Environmental Protection Agency
Office of Policy, Planning, and Evaluation
Office of Research and Development

October 1988

DRAFT

CHAPTER 10

AGRICULTURE

FINDINGS

Although climate change is not likely to threaten U.S. food supplies, it will affect crop yields and result in a northward shift in cultivated land, causing significant regional dislocations in agriculture with associated impacts on regional economies. It will expand crop irrigation requirements, stress livestock production, and increase infestations of agricultural pests and diseases.

Crop Yields

- The effects of climate change alone may reduce average yields of corn, soybeans, and wheat, both rainfed and irrigated, except in the northernmost latitudes where warmer conditions provide a longer frost-free growing season. Decreases in modeled yields result primarily from higher temperatures, which shorten a crop's life cycle.

- When the direct effects of CO_2 on crop photosynthesis and transpiration are approximated along with the effects of climate change, average rainfed and irrigated corn, soybeans, and wheat yields could overcome the negative effects of climate change in some locations. If climate changes are severe, yields could decline. Whether these modeled results will be reproduced under field conditions is uncertain.

- Even if the patterns of climate variability are unchanged, yield stability may decrease, particularly under rainfed conditions. This may occur because there would be more days above temperature thresholds for particular crops. The exact magnitude of change will be sensitive to changes in climatic variability.

Economic Impacts

- There may be a small to moderate aggregate reduction in the nation's agricultural output. Production appears to be adequate to meet domestic consumption needs.

- Assuming no change in export demand, reduced outputs would decrease exports, which could negatively affect global food supplies and the U.S. trade balance. This report did not analyze global changes in agriculture.

- Under the most severe climate change scenarios, continued technological improvements, similar to those in recent years, would have to be sustained to offset losses.

- The economic response of agriculture to shifts in regional productivity may be to shift crop production and associated infrastructure in a northward direction. It is not possible to determine if corn and soybean production could be sustained in northern areas, because soil conditions and other factors were not analyzed.

Irrigation Demand

- The demand for irrigated acreage is likely to increase in all regions. This is due to the reliability of irrigated yields relative to dryland yields and to higher commodity prices that make expansion of irrigated production more economically feasible. This result is sensitive to whether the cost of water to farmers increases.

- More irrigation may increase stress on and competition for regional water supplies. Increased irrigation also implies associated increases in surface and groundwater pollution and other forms of environmental degradation.

Agricultural Pests

- Climate warming could change the ranges and populations of agricultural pests. Temperature increases may enhance the survival of insect pests in the winter, extend their northward ranges, increase pest species with more than one generation per year, and allow pest establishment earlier in the growing season. These effects could result in a substantial rise in pesticide use, with accompanying environmental hazards.

Farm-Level Adjustments

- Farmers may adjust to climate change by using full-season and heat-resistant crop species or varieties, by altering planting dates, by planting two crops during one growing season, by increasing or altering their scheduling of irrigation, by using more pesticides, and by harvesting earlier. If climate change is not severe, these adjustments may mitigate losses in crop yields; more severe climate change is likely to make major adaptation necessary.

Livestock Effects

- Higher temperatures may increase disease and heat stress on livestock in some regions. Existing livestock diseases may shift north, while tropical diseases may extend their ranges into southern regions of the United States. Cold stress conditions may be reduced in the winter, but heat stress is likely to increase in the summer. Reproductive capabilities may also decrease.

Policy Implications

- Global climate change has important implications for all parts of the agriculture system. The agricultural research structure, which is dedicated to maintaining U.S. farm productivity, should enhance climate change research from the field level to the national policy level.

- Current U.S. Department of Agriculture (USDA) research on heat- and drought-tolerant crops and practices should be sustained and, possibly, enhanced to limit vulnerability to future climate change.

- The USDA should evaluate the implications of current legislation on the ability of agriculture to adapt to global warming by shifting the types of crops and location of farming. Such adaptation strategies should consider the impacts of soil erosion and water quality.

- The USDA, the Department of Commerce, the U.S. Trade Representative, and the State Department should consider the implications of potential long-term changes in the level of U.S. crop exports for the U.S. balance of trade and strategic interests.

- There is an urgent need for a national drought policy to coordinate Federal response to the possibility of increased frequency and duration of future droughts. Even without climate change, such a policy is needed not only for the agricultural sector, but also for other sectors.

SENSITIVITY OF AGRICULTURE TO CHANGES IN CLIMATE

Agriculture is a critical American industry, providing food for the nation's population and as much as $42.6 billion in exports for the nation's trade balance (Figure 10-1). The industry employs 21 million people -- more than other industry, when taking into account workers on farms and in the meat,

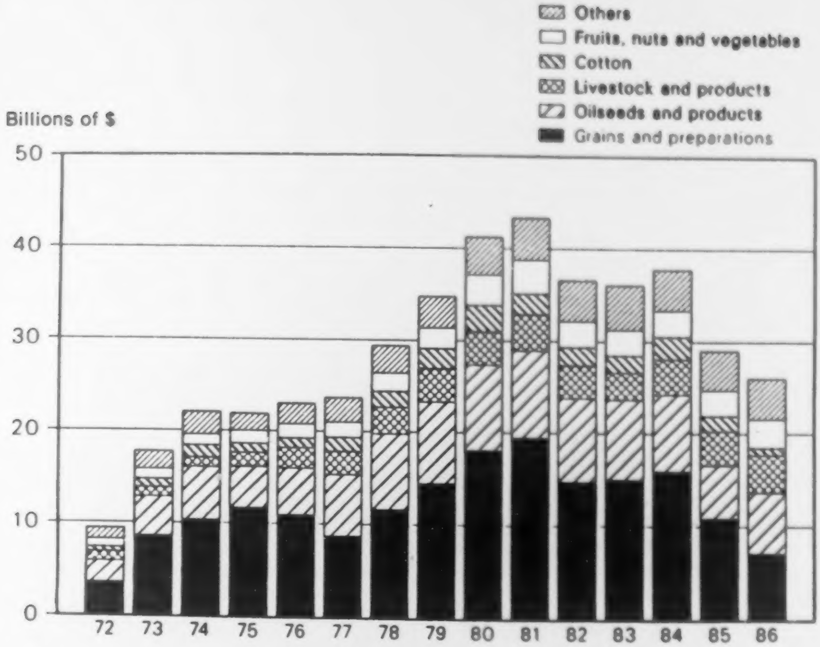


Figure 10-1. Value of U.S. agricultural exports by commodity.

Sources: The World Food Institute and U.S. Department of Agriculture, Economic Research Service, Foreign Agricultural Trade of the United States (Washington, DC), January-February 1987 and various other issues. Livestock excludes poultry and dairy products.

poultry, dairy, baking, and food processing industries (Council for Agricultural Science and Technology, 1988). The U.S. agricultural production system includes farm equipment manufacture, fertilizer and seed supplies, rural banking, and shipping. Total farm assets were $771 billion in 1985; food and fiber were 17.5% of the total gross national product in the same year. Wheat, corn, soybeans, cotton, fruits and vegetables, and livestock are among the most important U.S. agricultural commodities.

The study areas are major agricultural production regions (see Table 10-1). The Great Lakes and Southeastern States are major corn and soybean producers, while the Great Plains States grow mainly wheat and corn.

Worldwide, agricultural products must provide sustenance for the world's growing population, now estimated at about 5 billion and projected to rise to 8.2 billion by 2025 (World Bank, 1988). Global production and consumption of grain have grown steadily since 1960, although regional food shortages continue to occur due to climate variability and socioeconomic factors. Technological advances, such as improved hybrids and irrigation systems, have reduced the dependence of crop yields on the natural environment, but weather is still an important factor in agricultural productivity.

For example, during the Dust Bowl years of the 1930s, wheat and corn yields dropped by up to 50%. Midsummer 1983 saw an unpredicted drought in the U.S. Corn Belt and in the southeastern United States, causing the U.S. corn yields to fall by about a third, from over 7,000 kg/hectare (ha) to about 5,000 kg/ha. And failure of the monsoon season caused shortfalls in crop production in India, Bangladesh, and Pakistan in 1987. The 1980s have also seen the continued deterioration of food production in Africa, despite adequate world food supplies elsewhere, because of persistent drought, internal wars, poor distribution, weak infrastructure, and a deteriorating environment.

The 1988 drought demonstrated the impact that climate variability can have on agricultural productivity. This drought is expected to decrease corn yields by about 40%, and the cost of the 1988 Drought Relief Bill is estimated to be $3.9 billion (New York Times, 1988). The 1988 drought emphasizes anew the close link between agriculture and climate and the need to consider broadly the impacts of potential climate change on U.S. agriculture.

Future changes in climate due to increasing atmospheric trace gases, particularly CO_2, will affect agriculture because

Table 10-1. Crop Data by Region

	Corn	Wheat	Soybeans	Harvested Acres (thousands)
EPA Study Areas				
Southeast	311	272	306	29
Great Lakes	4,644	297	822	92
Great Plains	921	755	136	71
California	38	63	0.01	6
Total (48 States)	8,209	2,507	199	337

Units: Corn, wheat, and soybeans are in thousands of bushels; harvested acres are also in thousands.

Source: 1982 Census of Agriculture, Vol. 1, Geographical Area Series, Part 51, United States Summary and State Data. U.S. Department of Commerce, Bureau of the Census.

light from the sun, frost-free growing seasons, and the hydrologic cycle largely govern crop productivity. Livestock production will also respond to climate change through differing levels of heat and cold stress and altered ranges of disease-carrying vectors such as mosquitoes and ticks. Sea level rise, an associated impact of climate change, will threaten low-lying coastal agricultural regions with seasonal, and in some instances permanent, flooding, saltwater intrusion of freshwater aquifers and rivers, and salt contamination of soils. (See Water Resources chapter in this volume for linkages with agriculture.)

As predicted rises in temperature and other changes in climate variables such as precipitation occur, the higher levels of CO_2 in the air will also affect crops. Increasing CO_2 has boosted crop photosynthesis and has reduced the use of water by crops in experimental settings. Because experimental research has rarely dealt with both the climatic and the direct effects of CO_2 on plants simultaneously, it is difficult to assess the relative contributions of CO_2 and increased temperature to plant responses. This remains one of the most crucial questions in the analysis of impacts of climate change and increased CO_2 on agriculture.

Associated processes, such as changes in agricultural pests, may also play a role in responses of U.S. agriculture to climate change. The presence and abundance of pests affecting both crops and livestock are highly dependent on climate. The severity of the winter season, wind patterns, and moisture conditions determine in large part where pests will be prevalent. As these conditions change, the patterns, numbers, and types of insects also will change.

Much of U.S. agricultural production takes place under technologically advanced cropping systems that are primarily monocultural. Likewise, livestock production is highly specialized, both technically and geographically, and a high degree of integration exists between grain and livestock production. The economic robustness associated with general, multiple-enterprise farms has long since passed from the scene on any significant scale. Thus, the current vulnerability of our agricultural system to climate change may be greater in some ways than it was in the past.

Climate change and agriculture may affect the natural environment. As regional changes occur in crop and livestock production, these changes in agriculture may increase soil erosion, intensify the demand for water for irrigation, degrade water quality, reduce forested land, and destroy wildlife habitats. Other potential consequences are soil degradation, groundwater overdraft, loss of plant and aquatic communities, and reduced resilience in environmental resources in general. (See the Water Resources and Biological Diversity chapters of this report.)

Climate-driven changes in crop and livestock productivity cause changes in profitability and decisionmaking at the farm level, which in turn lead to shifts in farming systems at the regional level and in export-import supply and demand at the national level. Ultimately, impacts of climate change will reverberate throughout the global food economy, altering global food trade. Changes in U.S. agriculture will thus take place in a global context.

PREVIOUS STUDIES OF THE EFFECTS OF CLIMATE CHANGE AND AGRICULTURE

Relationships between climate and agriculture have been studied intensively for many years. However, relatively few studies have specifically addressed both the climatic and the direct effects that the growth in trace gases will have on agriculture. Even fewer studies have addressed these potential effects in an integrated approach that links both biophysical and economic spheres of analysis.

Most research attention in the United States has focused on the direct effects of CO_2 on crops, supported primarily by the U.S. Department of Energy. These studies are reviewed by Acock and Allen (1985) and Cure (1985) who found an average increase in yields of about 30% and increases in water-use efficiency for crops growing in favorable, current climate conditions between 330 and 660 ppm CO_2. Kimball (1985) and Decker et al. (1985) suggest that the potential effects of CO_2 and/or climate change on agricultural production systems may include shifts in production areas and changes in levels of livestock stresses, water availability, and pest control management.

Integrated approaches to the impacts of climate change on agriculture involving both biophysical and economic processes have been considered in studies by Callaway et al. (1982), the Carbon Dioxide Assessment Committee (1983), Warrick et al. (1986), and the Land Evaluation Group (1987). A benchmark international study on both the agronomic and economic effects of climate change on agriculture was conducted by the International Institute for Applied Systems Analysis (Parry et al., 1988). No study has as yet comprehensively examined the combined effects of climate change and the direct effects of CO_2 on U.S. agriculture.

Chapter 10

CLIMATE CHANGE STUDIES IN THIS REPORT

Structure of and Rationale for the Studies

The agricultural studies in this report involve the following research areas (see Table 10-2): (1) crop growth and yield, (2) regional and national agricultural economics, (3) demand for water for irrigation, (4) water quality, (5) pest-plant interactions, (6) direct effects of CO_2 on crop growth and yield, (7) impacts of extreme events, (8) potential farm-level adjustments, (9) livestock diseases, and (10) agricultural policy. The following studies were performed for this report:

Regional Studies

- Effects of Projected CO_2-Induced Climatic Changes on Irrigation Water Requirements in the Great Plains States -- Allen and Gichuki, Utah State University
- Climate Change Impacts upon Agriculture and Resources: A Case Study of California -- Dudek, Environmental Defense Fund
- Farm-Level Adjustments by Illinois Corn Producers to Climatic Change -- Easterling, Resources for the Future
- Impacts of Climate Change on the Fate of Agricultural Chemicals Across the USA Great Plains and Central Prairie -- Johnson, Cooter, and Sladewski, University of Oklahoma
- Impact of Climate Change on Crop Yield in the Southeastern U.S.A: A Simulation Study -- Peart, Jones, and Curry, University of Florida
- Effects of Global Climate Change on Agriculture: Great Lakes Region -- Ritchie, Baer, and Chou, Michigan State University
- Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study -- Rosenzweig, Goddard Space Flight Center/Columbia University

Table 10-2. Agriculture Projects for EPA Report to Congress on the Effects of Climate Change

Projects	Regional Studies				National Study
	California	Southeast	Great Lakes	Great Plains	
Crop Production	X	X	X	X	
Demand for Irrigation Water	X	X	X	X	
Water Quality			X	X	
Pest/Plant Interactions			X		
Farm-Level Management			X		
Regional/National Economics	X	X	X	X	X
Direct Effects of CO2	X	X	X	X	X
Livestock Pests & Diseases					X
Climatic Variability					X
Agricultural Policy					X

National Studies

- The Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment -- Adams, Glyer, and McCarl, Oregon State University
- Analysis of Climate Variability in General Circulation Models -- Mearns, Schneider, Thompson, and McDaniel, National Center for Atmospheric Research
- Direct Effects of Increasing CO_2 on Plants and Their Interactions with Indirect (Climatic) Effects -- Rose
- Potential Effects of Climatic Change on Plant-Pest Interactions -- Stinner, Rodenhouse, Taylor, Hammond, Purrington, McCartney, and Barrett, Ohio Agricultural Research and Development Center
- Agricultural Policies for Climate Changes Induced by Greenhouse Gases -- Schuh, University of Minnesota
- Changing Animal Disease Patterns Induced by the Greenhouse Effect -- Stem, Mertz, Stryker, and Huppi, Tufts University
- Effect of Climatic Warming on Populations of the Horn Fly -- Schmidtmann and Miller, Agricultural Research Service

Production of corn, wheat, and soybeans is critical to the economic well-being of the nation's farmers and the national trade balance. These crops make up about two-thirds of the total U.S. agricultural acreage, and their economic value is equal to that of all other crops combined. These three crops were selected for the modeling studies on the effects of climate change on yields.

The results from the regional studies of crop production (not including California), hydrological predictions from the climate models, and an agricultural economics model were linked in an integrated approach, to enable translation of the estimated yield changes from the crop modeling studies and predicted changes in water availability into economic consequences (see Figure 10-2). Such a coordinated analytical framework is necessary to account for the effects of market forces on the total agricultural sector, including livestock, and

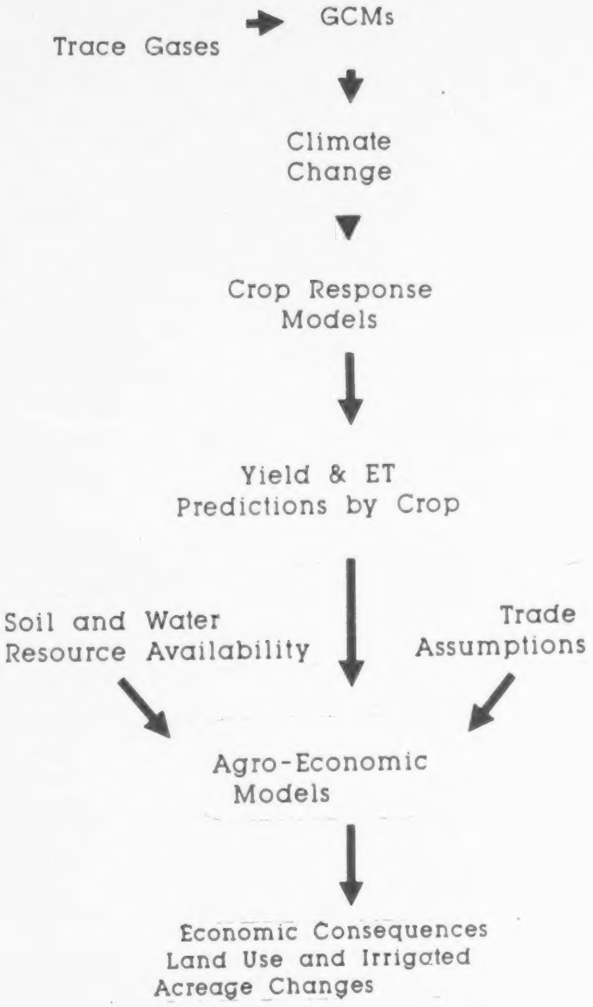

Trace Gases
GCMs
Climate Change
Crop Response Models
Yield & ET Predictions by Crop
Soil and Water Resource Availability
Trade Assumptions
Agro-Economic Models
Economic Consequences Land Use and Irrigated Acreage Changes

Figure 10-2. Flow chart of model interactions in EPA studies of the effects of global climate change on U.S. agriculture.

Source: Dudek (1987).

to evaluate the adequacy of the nation's resource base for agricultural production under climate change. Economic forces may lead farmers to grow more crops in areas with relatively high productivity and fewer crops in areas with relatively low productivity.

The studies of demand for irrigation water, water quality, and farm-level adjustment were also linked with the integrated modeling studies by common assumptions, sites, or outputs. Because California grows a large and diverse number of crop commodities, a simple approach was used to estimate crop yield changes for the California case study based on heat, sunlight, and photosynthetic response to CO_2. These yield changes were then used in a model of agricultural land and water use in California. Several adjustment experiments were included to test possible adaptation mechanisms, such as changes in planting dates and crop varieties.

The agricultural studies performed for this EPA report explore the sensitivities of the different parts of the agricultural system (shown in Table 10-1) to climate change scenarios. They are not meant to be predictions of what will happen; rather, they aim to define ranges and magnitudes of the potential responses as the systems are currently understood.

RESULTS OF AGRICULTURE STUDIES

Regional Crop Modeling Studies

Design of the Studies

Widely validated crop growth models -- CERES-Wheat and CERES-Maize (Ritchie and Otter, 1985) and SOYGRO (Jones et al., 1988) -- were used to simulate wheat, corn, and soybean yields at selected geographically distributed locations within the Great Lakes, the Southeast, and the Great Plains. California crop yield changes were predicted separately by using an agroclimatic index. (See the regional chapters of this report for specific results.) The crop models simulated both dryland and irrigated production systems. The crop modeling approach allowed for analysis of latitudinal gradients in changes in crop yields and provided compatible results for each climate change scenario to be used as input in the agricultural economics study. (See Ritchie et al., Peart et al., and Rosenzweig, Volume _.)

The direct effects of CO_2 -- i.e., increased photosynthesis and improved water-use efficiency -- were included with the climate change scenarios in some model runs to evaluate the combined effects. The direct effects were approximated by computing ratios of elevated CO_2 to ambient CO_2 values for daily photosynthesis and evapotranspiration rates (see Peart et al., Volume _).

Limitations

Uncertainties in the crop modeling studies reside in climate model predictions, locations of the climate stations (not always in production centers), crop growth models, and estimates of the direct effects of CO_2. In particular, the climate change scenarios did not include changes in climate variability, even though changes in the frequencies of extreme events may considerably affect crop yields. Technology and cultivars were assumed not to change from present conditions.

The direct effects of CO_2 in the crop modeling study results may be overestimated for two reasons. First, experimental results from controlled environments may show more positive effects of CO_2 than would actually occur in variable, windy, and pest-infested (weeds, insects, and diseases) field conditions. Second, because other radiatively active trace gases, such as methane (CH_4) also are increasing, the equivalent warming of a doubled CO_2 climate may occur somewhat before an actual doubling of atmospheric CO_2. A level of 660 ppm CO_2 was assumed for the crop modeling experiments, while the CO_2 concentration in 2060 is estimated to be 555 ppm (Hansen et al., 1988).

Results

Climate change scenarios alone, without the direct effects of CO_2, caused simulated yields of corn, soybeans, and wheat to decrease in the Great Lakes, Southeast, and Great Plains regions, except in the northernmost latitudes, where warmer conditions provide a longer frost-free growing season (Figure 10-3). The northern locations where yields increased included sites in Minnesota. Decreases in modeled yields resulted primarily from higher temperatures, which shorten the crop life cycle thus curtailing the production of usable biomass. Dryland modeled yields decreased more than irrigated yields.

When increased photosynthesis and decreased transpiration were included in the crop models along with the climate change scenarios, yields increased over the baseline in some locations but not in others (Figure 10-4). Particularly when combined with the hotter and drier GFDL climate change scenario, the direct effects of CO_2 did not fully compensate for changes in climate variables -- net yields decreased significantly from the base case.

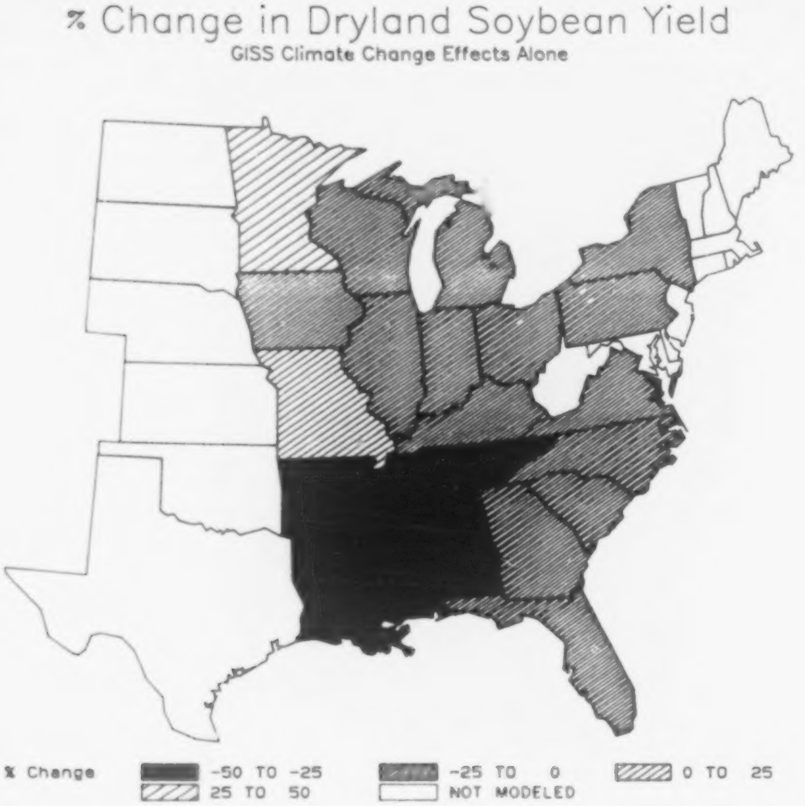

% Change in Dryland Soybean Yield
GISS Climate Change Effects Alone
% Change
-50 TO -25
-25 TO 0
0 TO 25
25 TO 50
NOT MODELED

Figure 10-3. Percent change in rainfed soybean yields simulated by the SOYGRO model with the GISS climate change scenario.

Source: Peart et al. and Ritchie et al., Volume ___.

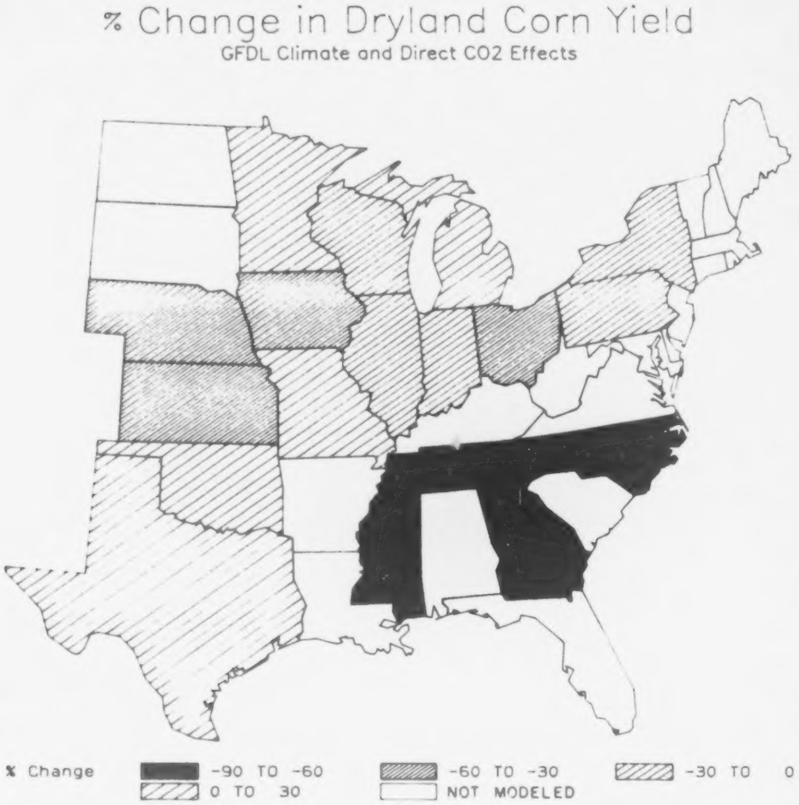

% Change in Dryland Corn Yield
GFDL Climate and Direct CO2 Effects
% Change
-90 TO -60
-60 TO -30
-30 TO 0
0 TO 30
NOT MODELED

Figure 10-4. Percent change in rainfed corn yields simulated by the CERES-Maize model for the GISS climate change scenario with approximated direct effects of CO_2 on photosynthesis and water use.

Source: Peart et al. and Ritchie et al., Volume ___.

The crop models were also used to test several possible adaptations by farmers to the predicted climate changes. For example, a corn variety that is better adapted to longer growing seasons was tested in Indiana. This later maturing variety did not compensate entirely for the yield decreases caused by the warmer climate change scenarios.

Implications

An implication of the crop modeling studies is that pressure for increased irrigation may grow in many agricultural regions. If the major agricultural areas are to continue to provide a stable supply of food under the predicted changes in climate, supplemental irrigation may be required for many soils. This could further tighten water supply problems in some areas and increase pollution from nonpoint sources (i.e., pollution that is not traceable to any one distinct source, such as agricultural pollution).

The water supply for the irrigation needed to stabilize production would come from both surface and subsurface sources, depending on the region. However, considerable uncertainty exists regarding the future availability of surface water and groundwater supplies with climate change, and concerning the costs of using or extracting the water. (See the Water Resources chapter of this report.)

Regional and National Economics Study

The estimated yield changes from the crop modeling studies and projected changes in irrigation water demand and availability were introduced into an agricultural economic model to translate the physical effects of climate change into economic consequences. Adams et al. (see Volume _) estimated the regional and national economic implications of changes in yields of wheat, corn, soybeans, and other crops and in the demand for and availability of water associated with alternative global climate change scenarios. In addition, sensitivity analyses on critical assumptions were also performed -- particularly for technological change and yield benefits due to the direct effects of increased CO_2.

Study Design

A spatial equilibrium agricultural model developed by Adams et al. (1984) was used to represent production and consumption of numerous agricultural commodities for the U.S. farm production regions as designated by the USDA (see Figure 10-5). The model has been used to estimate agricultural losses due to increased

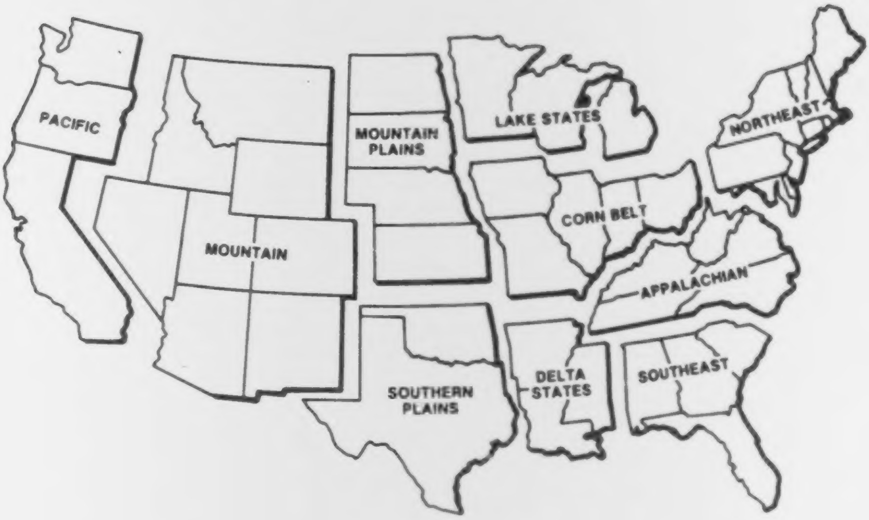

PACIFIC
MOUNTAIN
MOUNTAIN PLAINS
SOUTHERN PLAINS
LAKE STATES
CORN BELT
DELTA STATES
NORTHEAST
APPALACHIAN
SOUTHEAST

Figure 10-5. Farm production regions in the United States.

Source: USDA Economic Research Service (1987).

ultraviolet-B (UV-B) radiation caused by stratospheric ozone depletion (Adams et al., 1984). It consists of farm-level models for production regions, integrated with a national-level model of the agricultural sector. Both irrigated and nonirrigated crop production and water supply relationships are included for most regions. The model stimulates a long-run, perfectly competitive equilibrium, and was developed using 1980-83 economic and environmental parameters.

Limitations

The economic approach used in this study has several limitations. The economic model is static in the sense that it simulates an equilibrium response to climate change, rather than a path of future changes. Substitution of appropriate crop varieties and adjustments in farm management techniques were not included, thus possibly overestimating the negative effects of climate change. Estimates of the beneficial direct effects of CO_2 on crop yields may have biased results in the positive direction. Furthermore, changes in yields used as inputs to the economic model were only modeled for wheat, corn, and soybeans for a limited number of sites and regions, and national estimates were derived from these for all other crop commodities in the model. This introduces uncertainties into the results.

Potential changes in international agricultural supply, demand, and prices due to climate change are not explicitly included in the model. Such changes could have major impacts on U.S. agriculture.

Results

The economic model showed a small to moderate aggregate loss in economic welfare associated with the projected crop yield and hydrologic changes derived from the climate change scenarios (see Table 10-3). For the moderate climate change scenario, net losses were small; for the more extreme scenario, they were greater.

Production of most crops was reduced because of yield declines and limited availability of land and resources. The largest reductions were in sorghum (-20%), corn (-13%), and rice (-11%), because these estimated losses are equivalent to 5 and 28% of the 1982 value of crop and livestock commodities produced in the United States. The magnitudes of these changes, which are annual, may be compared to the estimated $6 billion cost of the Drought Relief Bill for 1988. In general, consumers lose and producers gain due to the increased prices of agricultural

Table 10-3. Aggregate Economic Effects of GISS and GFDL 2xCO_2 Global Climate Change on U.S. Agriculture (in billions of 1982 dollars)

Run	Economic Effects		
	Consumers	Producers	Total
GISS Analysis 4[a]	-7.3	+1.5	-5.0
GFDL Analysis 4	-37.5	+3.9	-33.6

[a] Analysis 4 includes the crop yield and irrigation water supply and demand consequences of climate change throughout the United States.

Source: Adams et al., Volume _.

commodities and inelastic demand (insensitivity to price changes) for agricultural crops.

Agricultural activity would shift northward with both GISS and GFDL climate change scenarios (see Figure 10-6). Land under production in Appalachia, the Southeast, the Mississippi Delta, and the Southern Plains, could decrease by 5 to 25%, while in the Lake States, the Northern Plains, and the Pacific it could increase by 5 to 17%. Irrigated acreage is estimated to increase in all areas, primarily because irrigation becomes economically feasible as agricultural prices rise (see Figure 10-7). Demand for additional water may be met in part by increased groundwater pumping, although this could be a matter of concern in areas where groundwater is already being overdrawn. Since changes in precipitation and recharge patterns are likely with climate change, the availability of groundwater and the costs to extract it might also be affected (see chapter on Water Resources).

The impact of higher CO_2 levels on crop productivity would probably reduce the negative economic impacts of climate change on the agricultural sector (Table 10-4). Under the less severe GISS climate scenario, the CO_2 direct effects would sufficiently counter the climatic effects in most regions, so that the net effect would be a gain in economic welfare. Consumers would be the primary beneficiaries, though (in aggregate) producers would also gain slightly. However, because the climatic effects on crops differ by region, the output of some regions would increase, while that of others would decrease. With the more severe GFDL climate change scenario combined with the direct effects of CO_2, economic welfare still would decrease, but not by as much as it did with the climate change scenarios alone. Here, consumers would be the losers.

Technological change, such as higher yielding crop varieties, chemicals, fertilizers, and mechanical power, has historically enabled agriculture to increase production with the same amount of or less land, labor, and other resources. When the effect of future technological change was modeled along with the less severe GISS climate change effects (without the direct effects of CO_2), most of the adverse climate effects were offset. Under the severe GFDL climate change scenario, continued and substantial improvements in yields would be required to overcome the climate change effects. Stated another way, the adverse effects of climate change would negate most of the higher output attributable to improved technology over the next 50 years.

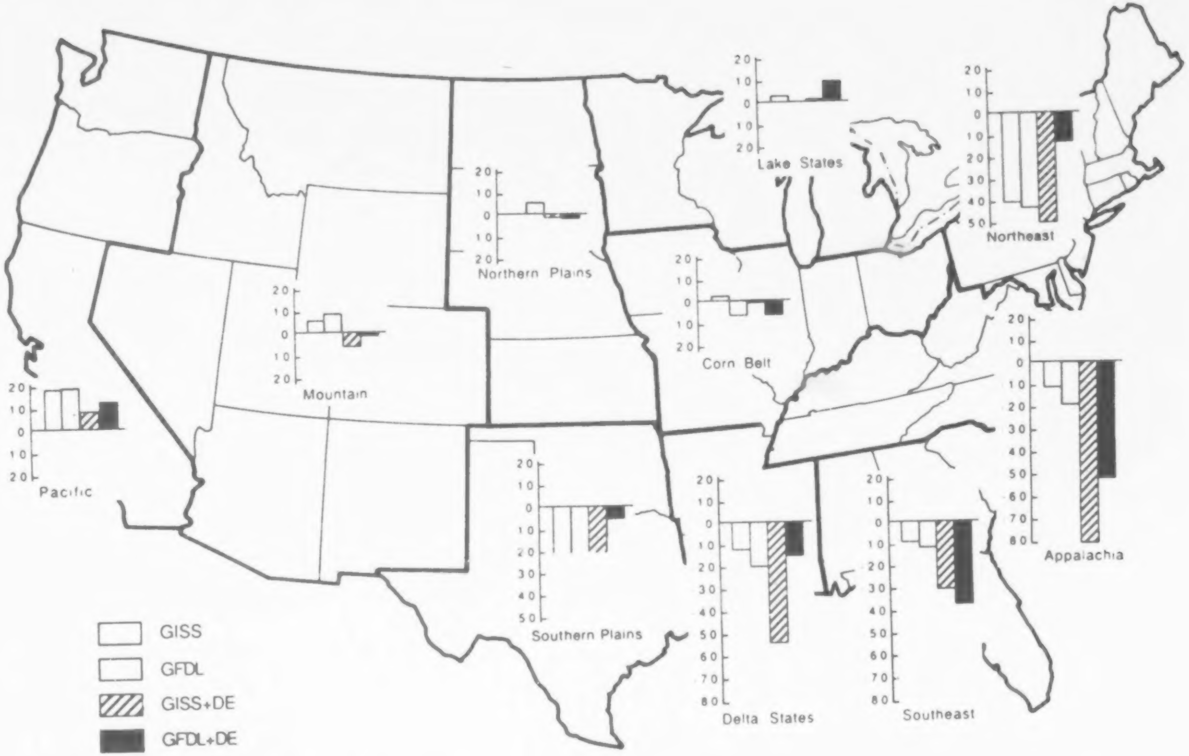

Pacific
Mountain
Northern Plains
Southern Plains
Lake States
Corn Belt
Delta States
Southeast
Appalachia
Northeast
GISS
GFDL
GISS+DE
GFDL+DE

Figure 10-6. Percent change in regional agricultural acreage simulated by an economic model of the U.S. agricultural sector for the GISS and GFDL climate change scenarios with and without the direct effects of CO_2 on crop yields.

Source: Adams et al., Volume _.

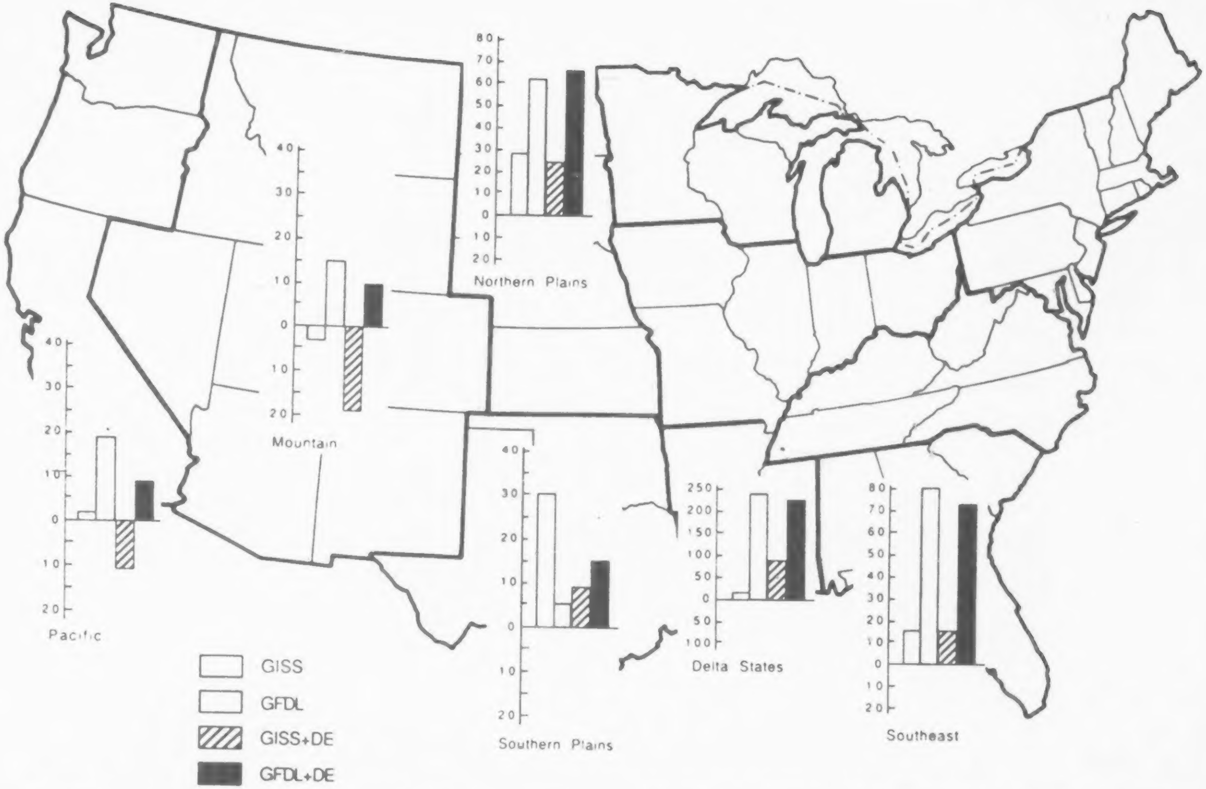


Figure 10-7. Change in regional irrigation acreage simulated by an economic model of the U.S. agricultural sector for the GISS and GFDL climate change scenarios with and without the direct effects of CO_2 on crop yields.

Source: Adams et al., Volume _.

Table 10-4. Combined Effects of Direct CO_2 and Climate Change on Agriculture: GISS and GFDL Analyses 4

Run	Economic Effects		
	Consumer	Producer ($ billion)	Total
GISS Analysis 4: without CO_2	-7.3	1.5	-5.9
GISS Analysis 4: with CO_2	9.4	1.3	10.6
GFDL Analysis 4[a]: without CO_2	-37.5	+3.9	-33.6
GFDL Analysis 4: with CO_2	-10.3	0.6	-9.7

[a] Analysis 4 includes the crop yield and irrigation water supply and demand consequences of climate change throughout the United States.

Source: Adams et al., Volume _.

Chapter 10

Implications

Food Supply

Although climate change could reduce the productive capacity of U.S. agriculture, the reduction does not imply major disruption in the supply of basic commodities for American consumers. Domestically, consumers would face slightly to moderately higher prices under some analyses, but supplies would be adequate to meet current and projected domestic demand. However, most exported commodities in some scenarios decline by up to 70%, assuming the demand for exports remains constant.

While climate change does not appear to be a food security issue within the United States, supply and demand for agricultural commodities could shift among international regions. Responses of U.S. agriculture would take place in this global context. These changes in global agriculture cannot be determined without analyzing the potential impacts of climate change on both major world agricultural production regions and potentially vulnerable food deficit regions.

Regional Economics and Land Use

Regional shifts in U.S. agricultural production patterns are highly likely, as all analyses showed a consistent northward shift in the production of the major commodities of wheat, corn, and soybeans (see Figure 10-6). Other crops, including specialty crops such as vegetables and fruits, could also shift. Where agricultural acreage declines, this might further weaken an economic base already under pressure from long-term structural changes in U.S. agriculture.

Environmental Concerns

Regional agricultural adjustments could place environmental resources at risk. Where agricultural acreage would increase, demands for natural resources, such as soil and water, might intensify current pressures on environmental elements, such as rivers, lakes, aquifers, wetlands, and wildlife habitats. Northern States, such as Minnesota and North Dakota, could become more productive for annual crops like corn and soybeans because of warmer temperatures and a longer frost-free growing season. Because of the presence of forests and wetlands in these regions, increased agricultural production in the area might threaten natural ecosystems, including wildlife habitats such as prairie potholes for ducks and flyways for bird migrations.

In addition, many of the glacial till soils in the northern latitudes are not as productive as Corn Belt soils. Thus, large increases in production of crops would most likely require increased applications of chemical fertilizers. The use of these fertilizers in humid regions on glacial till and sandy soils is now creating an environmental hazard to the underlying groundwater, receiving waters, and aquatic habitats in many areas. With climate change, water and fertilizer use would have to be carefully managed to minimize still more leaching of water-soluble nutrients such as nitrogen and potash, while continuing to provide enough nutrients for crop growth.

Demand for Water for Irrigation

Water is the single most critical factor in determining the development, survival, and productivity of crops. The amount of water that crops use and thus the demand for irritation water are governed largely by the evaporation process. The projected higher air temperatures due to increasing trace gases in the atmosphere could heighten evaporative demands. Farmers may irrigate more to satisfy these higher demands, which could accelerate depletion of groundwater and surface water resources. Also, the rate of evaporation might outstrip precipitation, thus decreasing crop yields.

Studies reported in the California and the Great Plains case studies (see Chapters 4 and 5) explicitly examined the potential changes in demand for water for irrigation. In these regions, water is a critical resource for agriculture; California and the parts of the Great Plains fed by the Ogallala Aquifer, in particular, depend very heavily on irrigation for crop production.

Irrigation Requirements in the Great Plains

Allen and Gichuki (see Volume _) computed irrigation water requirements for sites in the Great Plains for the baseline climate and the GISS and GFDL climate change scenarios. The direct effects of CO_2 and water use were also included. (See Chapter 7, Great Plains, for study design and limitations.) Major changes in irrigation water requirements were observed at all locations in the Great Plains, for all crops (see Figure 10-8). The most significant were the persistent increases in seasonal net irrigation water requirements for alfalfa, which were driven by the climate changes in temperature, wind, humidity, and solar radiation, and by the lengthening of the growing season. Decreases in irrigation requirements were observed for winter wheat and corn in most regions. These decreases were attributed to earlier planting dates and the shortening of the crop-growing

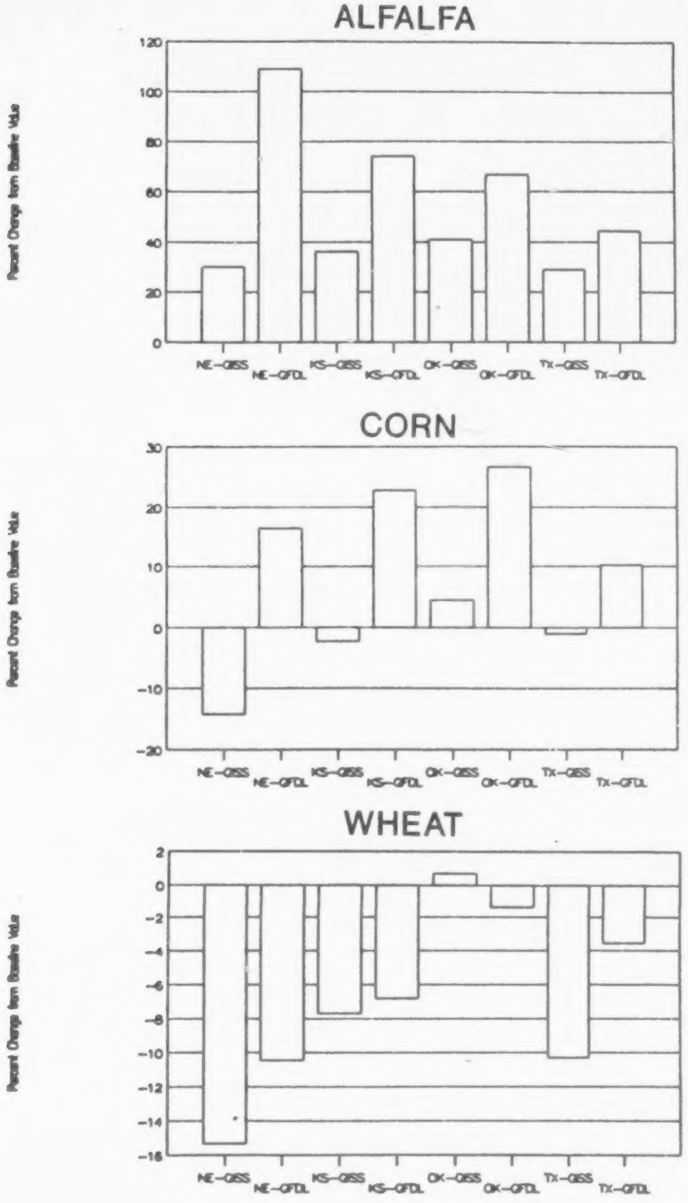


Figure 10-8. Percent change in net seasonal irrigation requirements with a 20% increase in bulk stomatal diffusion resistance.

Source: Allen and Gichuki, Volume __.

season by high temperatures. When crop varieties appropriate to the longer growing season were modeled, irrigation water requirements for winter wheat increased. Irrigation water requirements during peak periods increased in almost all areas (see Figure 10-9).

While farmers in the Great Plains would probably shift to longer season crops, the predicted climate conditions (warmer temperatures and predicted drying in some areas) during the later summer months could increase irrigation requirements and elevate leaf temperatures to a point that exceeds optimum temperatures required for high productivity. This might make it uneconomical to take full advantage of the predicted longer growing season, especially if the higher CO_2 levels increase photosynthesis and offset the effects of a shorter season to some degree.

Water Resources for Agriculture in California

In the California regional case study, Dudek (see Volume _) characterized the potential shifts in demand for water for agricultural production that would accompany shifts in cropping patterns driven by changing climate. (See California chapter for study design and limitations.) When climate change was considered alone, groundwater extraction and surface water use declined in California as a result of changes in both supply and demand. When the direct effects of CO_2 on crop yields were included, however, groundwater extraction increased due to improved yields of all crops except corn and to enhanced economic welfare. Institutional responses to changes in surface and groundwater use include water transfers, which improve irrigation efficiency. When water markets were included in the simulations, economic welfare was improved by 6-15% over the base, while crop acreage increased and groundwater extraction decreased.

Implications for Demand for Water for Irrigation

Expanded use of irrigation is implied from the regional crop modeling studies for the Great Lakes, the Southeast, and the Great Plains (see Chapters 5, 6, and 7). Increases in irrigated acreage are also predicted for most regions when the economics of crop production are factored in (see Adams et al., Volume _). When these results are considered along with the other Great Plains and California studies, it appears that climate change is likely to increase the demand for irrigation.

In the Great Plains, heightened evaporative demand and variability of rainfall may increase the need for irrigation in dryland farming regions. The projected changes in irrigation water requirements are varied, and specific crops and locations

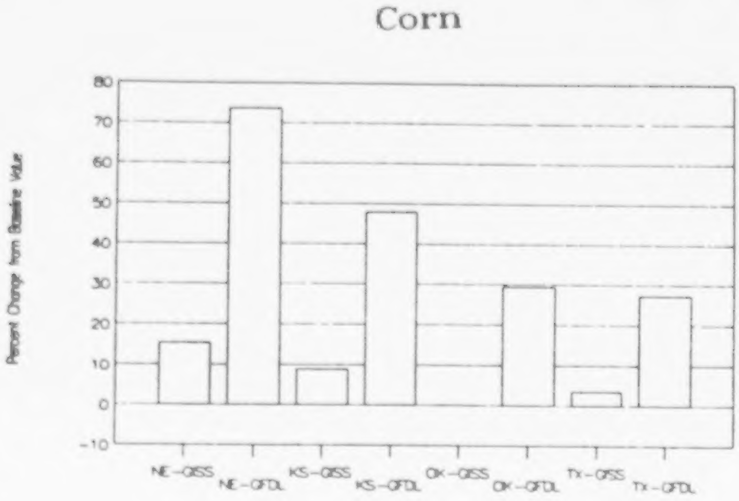


Figure 10-9. Percent change in peak irrigation requirements of corn with a 20% increase in bulk stomatal diffusion resistance.

Source: Allen and Gichuki, Volume _.

probably will be affected differently. Higher peak irrigation water requirements for some crops may require larger capacity irrigation systems and enlarge energy demands.

Intensified extraction of water poses serious environmental and economic problems, especially in areas where groundwater is being overdrawn. Streamflows also may slacken if more surface water is used for irrigation, thereby aggravating water quality problems. This in turn would harm fish, wildlife, and recreational activities.

Regional changes in cropping locations and patterns of water use also could exacerbate agricultural, nonpoint source pollution and further deplete groundwater resources. Institutional responses, such as markets for water transfers, could help improve irrigation water management and alleviate some of these negative effects.

The economic and social costs of shifting the location of irrigated agriculture could be considerable. The construction of irrigation systems consisting of reservoirs, wells, ditches, pipes, pumps, and sprinklers currently requires about $1,500-5,000 per hectare (ha) in capital investment (Postel, 1986).

Direct Effects of CO_2 on Crops

Global increases in CO_2 are expected to influence crop metabolism, growth, and development directly through physiological processes and indirectly through climate. Rose (see Volume _) reviewed recent experimental work performed on the direct effects of CO_2 on crops, with emphasis on wheat, corn, soybeans, and cotton.

Elevated concentrations of CO_2 directly affect plant processes such as photosynthesis and transpiration. CO_2 concentrations are also expected to influence these processes indirectly through predicted increases in temperature and other changes in climate variables such as precipitation. Because experimental research has rarely simultaneously studied both the direct and indirect effects of plant responses, it is difficult to assess the relative contributions of elevated CO_2 and climate changes to predictions of crop responses.

Research on the physiological effects has focused primarily on responses of rates of photosynthesis and transpiration to increasing concentrations of atmospheric CO_2. Photosynthesis rates have increased in these crops in relatively ideal experimental environments. At moderate temperatures, most crops will probably show increases in size and possibly yield as CO_2

concentrations rise. However, plants also have internal regulation mechanisms that may lessen these effects under field conditions.

Transpiration rates per unit leaf area decrease, while total transpiration from the entire plant sometimes increases because of greater leaf area. Drought-stressed plants exposed to high partial pressures of CO_2 should be better able to cope with water deficits. Leaf temperatures in all species are expected to rise even more than air temperatures, which may inhibit plant processes that are sensitive to high temperature.

Few studies have examined the interactive effects of CO_2, water, nutrients, light, temperature, pollutants, and sensitivity to daylength on photosynthesis and transpiration. Even fewer studies have examined the effects of these interactions on the growth and development of the whole plant. Therefore, considerable uncertainty exists concerning the extent to which the beneficial effects of increasing CO_2 will be seen in crops growing in the field under normal farming conditions with climate change.

Climate Impacts on Pest-Plant Interactions

Compared to the existing information on the potential effects of climate change on crop production, relatively little effort has been directed toward assessing the influence of climate change on plant-pest interactions. Atmospheric increases in temperature and CO_2, and changes in moisture regimes, all can directly or indirectly affect interactions between pests and crops.

Study Design and Results

Stinner et al. (see Volume _) conducted a literature survey and modeling experiments on the major mechanisms through which climate change may affect pest-plant interactions. This study emphasized the major insect pest and pathogen species of corn and soybeans. The survey indicated that temperature and precipitation patterns are the key variables that affect crop-pest interactions. The temperature increases associated with the climate change scenarios bring about the following trends: (1) increased survival for migratory and nonmigratory insect pest species in the winter, (2) northern range extensions of current pests in the higher latitudes and migration of southern species into the northern Grain Belt regions, (3) an increase in pest species with more than one generation per year in the northern

Grain Belt, (4) earlier establishment of pest populations in the growing season, and (5) increased abundance of pests during more susceptible growth stages of crops.

The potential changes in the overwintering ranges of four major pests were mapped for the GISS and GFDL climate change scenarios and were compared to present ranges. The overwintering capability of the four major pests may extend northward with both climate change scenarios. For example, the potato leafhopper, a serious pest on soybeans and other crops, at present overwinters only in a narrow band along the coast of the Gulf of Mexico (Figure 10-10). Warmer winter temperatures predicted by both the GFDL and GISS models suggest a doubling or tripling of the overwintering range in the United States, respectively. Increases in the winter population density of this size would increase the invasion populations in the northern States by similar factors. The invasions also would be earlier in the growing season, assuming planting dates do not change. Both features are likely to lead to greater insect density and damage. This pattern is repeated with the other three pests studied and indicates that these pests, and possibly others, may move northward and invade cropping systems earlier in the growing season under climate change conditions.

The Soybean Integrated Crop Management (SICM) model (Jones et al., 1986) was run with the GISS and GFDL climate change scenarios to estimate changes in damages caused by corn earworm. Modeling results show that earworm damage to soybeans will increase in severity in the Grain Belt under a warmer climate. Such damage could cause grain farmers in the Midwest to suffer significant economic losses. These results were particularly marked with the warmer and dryer GFDL scenario.

Study Limitations

Lack of knowledge about the physiological effects of CO_2 on crop plants and lack of experimental evidence on direct effects of CO_2 on insect-plant interactions make the study of pest-plant interactions particularly difficult. Only one cultivar is used in the modeling study under both the baseline and the climate change scenarios. In reality, farmers would probably switch to a more climatically adapted cultivar as climate changed.

Study Implications

Increased pest-related crop damage could intensify pesticide use. The economic and environmental ramifications of such an increase could be substantial, not only in current farming regions but also in new areas as agriculture shifts to the more

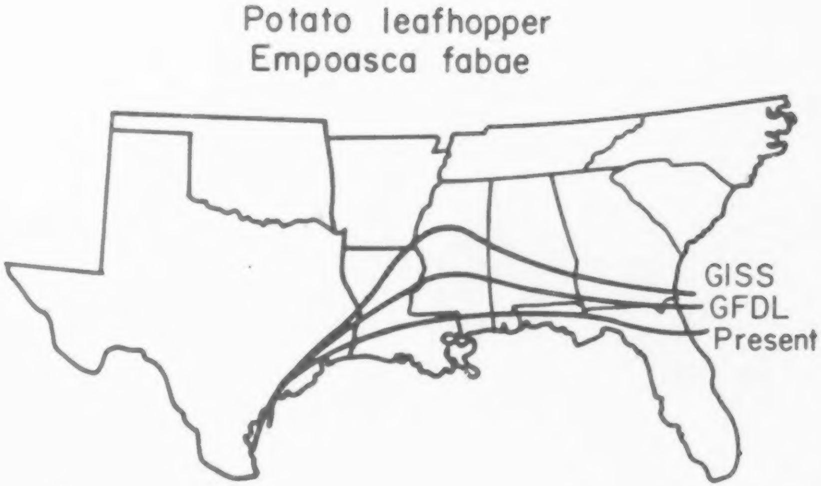

Potato leafhopper
Empoasca fabae
GISS
GFDL
Present

Figure 10-10. Present and potential (GISS and GFDL climate change scenarios) overwintering range of the potato leafhopper, Empoasca fabae, a major pest of soybeans.

Source: Stinner et al., Volume __.

northern regions such as the Northern Plains, the Great Lakes States, and the Pacific Northwest (see Figure 10-6).

Increased use of pesticides would create additional threats to the integrity of ecosystems through soil and water contamination and could increase risks to public health. If agricultural production is not to rely increasingly on chemicals that are potentially harmful to the environment, an increased need will exist for alternative pest management strategies such as biological control, genetic resistance, and innovative cropping systems.

Effects of Climate Change on Water Quality

Agricultural pesticides are ranked as a high priority pollution problem in many rural regions. Potentially toxic agricultural chemicals can be transported away from fields via runoff of surface soils and via downward leaching and percolation through the soil. An understanding of these processes is essential to the evaluation of potential threats to drinking water quality caused by climate change.

Study Design

Johnson et al. (see Volume _) modeled the partitioning of agricultural pesticides among uptake, degradation, surface runoff, and soil leaching for wheat, corn, and cotton production regions in the Great Plains and the Corn Belt. (See the Great Plains chapter of this report for details of the study.) They used the Pesticide Root Zone Model (PRZM) (Carsel et al., 1984), which simulates the vertical movement of pesticides in the soil. The model consists of hydrological and chemical transport components that simulate runoff, erosion, plant uptake, leaching, decay, foliar washoff, and volatilization of a pesticide. The interactions among soil, tillage, management systems, pesticide transport, and climate change were studied.

Limitations

The frequency and duration of precipitation remain the same in the climate change scenarios, even though these storm characteristics are critical factors in determining the transport of agricultural chemicals and may change. The scenarios assume that the number of days with rainfall does not change, but the intensity of rainfall increases or decreases. Runoff and leaching estimates would most likely be different if the number of days of rainfall changed and daily rainfall amounts were held constant.

The PRZM is a one-dimensional, point model that does not simulate the transport of water below the root zone. Thus, results on a regional basis must be extrapolated with care. The direct effects of CO_2 on crop growth, which may increase the size of the plants and the extent to which crops cover the soil, are not included.

Results

Regional changes in chemical loadings of water and sediment are likely but probably will not be uniform. There appears to be some consensus between the GCM scenarios concerning the estimated regional changes (Table 10-5). Modeled pesticides in runoff increase in the cotton production area, and pesticides carried by sediments decrease in the spring wheat and corn regions. Leaching of pesticides tends to be less everywhere owing to changes in seasonal precipitation and increased evaporation.

Implications

When the changes in water quality from the predicted climate change scenarios are considered in conjunction with the predicted increases in pests and implied higher applications of pesticides described in the study on pest-plant interactions, the potential for changes in the nation's water quality becomes apparent. Any deterioration in water quality could adversely affect public drinking water supplies and human health.

Climate Variability

The impacts of climate change result not only from a slow change in the mean of a climate variable but often from shifts in the frequency of extreme events. Droughts, freezes, and prolonged periods of hot weather have strong effects on agricultural production. While the agricultural modeling studies did not include the effects of potential changes in climate variability, Mearns and Schneider (see chapter on Climate Variability in this report) reviewed literature on agriculture and extreme events to determine the nature and magnitudes of significant impacts.

Corn, soybeans, wheat, and sorghum are sensitive to high maximum temperatures during blooming. Lower yields of corn, wheat, and soybeans have been found to be correlated with high temperatures. The damaging effect of runs of hot days on corn yields was particularly evident in 1983 in the U.S. Corn Belt.

Although low temperatures may be less of a problem with the predicted climate change, risks of frost damage to crops may

Table 10-5. Summary of GCM Model Consensus of PRZM Pesticide Transport by Cropping Region and Pesticide[a]

	Surface Pesticides Runoff Losses	Surface Pesticide Erosion Losses	Pesticide Leaching
SPRING WHEAT:			
Highly soluble/short-lived[b]	+	+	-
Highly soluble/long-lived		+	-
Slightly soluble/long-lived			-
WINTER WHEAT:			
Highly soluble/short-lived		+	+
Highly soluble/long-lived	+		-
Slightly soluble/long-lived			-
COTTON:			
Highly soluble/short-lived	+		+
Highly soluble/long-lived	+	+	-
Slightly soluble/long-lived	+	+	-
CORN:			
Highly soluble/short-lived	-	-	
Highly soluble/long-lived		-	-
Slightly soluble/long-lived	-	-	-

[a] + indicates that median values increase under climate change; - indicates that median values decrease under climate change; blank indicates no consensus among median values.

[b] ex. median value of all tillage, soil, weather site scenarios for highly soluble/short-lived pesticides in the spring wheat crop area.

Source: Johnson et al., Volume _.

change in the growing areas of certain crops. Citrus trees are very vulnerable to low minimum temperatures. Winter wheat is often damaged by low temperatures known as winter kill, especially in the absence of snow. (See Glantz, Volume _, for a discussion of how the Florida citrus industry adapted to increased frequency of freezes in the 1980s.) Even with warmer winters and fewer frosts, more damage can occur at less extreme temperatures. For example, the effect of freezing temperatures is exacerbated if the crops have not yet been hardened by the cold, or if they are no longer dormant and a cold snap occurs.

Drought is a major cause of yearly variability in crop production. In the Dust Bowl years of the 1930s, yields of wheat and corn in the Great Plains dropped to as much as 50% below normal. In 1988, agricultural disaster in areas of the northern Great Plains demonstrated a high vulnerability to drought; and nationwide a nearly 40% decrease in U.S. corn yields is predicted. Reduction in vegetative cover associated with drought also brings about severe wind erosion of soils, which will affect future crop productivity. Low yields of forage crops during droughts result in food shortages for livestock and premature selling of livestock.

Farm-Level Management and Adjustments to Climate Change

Adjustments to existing production practices are the first course of action in the face of climate change. The net effect of climate change with adjustment by farmers may be significantly different from the estimated effects of climate change alone.

Study Design

Several studies addressed possible adjustments that could modify the effects of climate change. These adjustments include changes in planting and harvesting dates, tillage practices, crop varieties, application of agricultural chemicals, irrigation technology, and institutional responses for management of water resources.

Results of Adjustment Studies

Ritchie et al. demonstrated that the yield reduction in corn in the Great Lakes can be partly overcome with selection of new cultivars that have a longer growing season (see Great Lakes chapter of this report). Rosenzweig (see Great Plains chapter of this report) showed that adjusting the planting date of winter wheat to later in the fall did not ameliorate the effects of climate change, but that changing to varieties more suited to the predicted climate overcame yield decreases at some locations.

Dudek's California study found that flexible institutional responses to climate change helped to compensate partly for negative climate change effects (see California chapter of this report). By allowing movement of water around the State by transferring water rights, California water resource managers can alleviate some groundwater extraction and compensate for surface water reductions.

Easterling (see Great Lakes chapter of this report) found that potential farmer adjustments to climate change include changes in tillage practices, increased fertilizer application, more full-season and heat-resistant varieties, changes in planting densities, higher pesticide use, earlier harvest, and less artificial drying. Different adjustments would occur at different times in the cropping season. With the hotter and drier GFDL scenario, farmers may be forced to adopt production practices that are different from those in use today. Climate changes that leave soils drier during summer than they are at present will most likely lead to increased use of irrigation in the Corn Belt. This increased use of irrigation is also supported by the projected price increases for all crops grown in Illinois.

Implications of Adjustment Studies

Although detrimental climate change effects on agriculture may be partly offset naturally by increased photosynthesis and water-use efficiency caused by higher levels of atmospheric carbon dioxide, farmers will no doubt use a variety of adjustments to adapt to climate change. Market forces also will aid adaptation to climate change because they help to allocate resources efficiently.

More severe climate changes are likely to necessitate major adaptations, such as farm abandonment in some regions. Prior investments may be lost as existing infrastructures become obsolete and new investments are needed for new locations. Some of these adjustments could be costly.

Improvements in agricultural technology also may be expected to ease adjustment by development of appropriate farming practices and crop variety and livestock species. Adjustment and adaptation to climate change should be included in agricultural research programs to enable this process to occur.

Livestock

Animal products are a critical source of protein, energy, vitamins, and minerals. U.S. livestock production, mainly from cattle, swine, sheep, and poultry, was estimated to be worth over $31 billion in 1986 (USDA, 1987).

Climate is known to significantly affect many aspects of animal health and production. The direct effects of climate change on animal health include differences in incidence of heat and cold stress, changes in weight gain, and decline in reproductive capabilities. Indirect effects may involve trends in agricultural commodities, such as the availability and prices of types of animal feeds and the expanded geographic distribution and activity of disease-carrying vectors.

Higher winter temperatures may lower the incidence of respiratory diseases in livestock (Webster, 1981). Conversely, warmer summers may necessitate more hours of indoor cooling during which pathogens are confined to housing structures. Climate warming may significantly increase the costs of air-conditioning in poultry housing. Changes in reproductive capabilities such as decreased ovulation rates, shortened intensity and duration of estrus, decreased fertility of males, and increased embryonic mortality also have been shown to occur with high temperatures (Ames, 1981).

Climate change may also affect the survivability, activity, and geographic distribution of vectors responsible for the transmission of infectious diseases in livestock. The activity and reproduction of disease-carrying vectors infecting livestock, humans, and crops are driven primarily by temperature, humidity, and precipitation. These impacts are likely to be similar to those on mortality and morbidity of disease in humans (see chapter on Human Health, this volume), and they also are similar to changes predicted for crop pests.

Design of Livestock Studies

Stem et al. (see Volume _) studied the available literature on four diseases to evaluate the range of potential changes in disease distribution and occurrence under climate change conditions. Schmidtmann and Miller (see Volume _) used a population dynamics simulation model to estimate the effects of the GFDL climate change scenario on the life cycles of the horn fly, a ubiquitous pest of pastured cattle throughout the United States.

Results of Livestock Studies

Stem et al. found that, under warmer conditions, livestock diseases currently causing serious economic losses in tropical countries could spread into the United States. Rift Valley fever is transmitted principally by mosquitoes, and danger of the disease may spread as rising winter temperatures become able to support an active increase in the mosquito population. African swine fever also may become more of a threat.

The ranges and activities of disease-carrying agents of blue tongue and anaplasmosis, diseases currently causing severe losses in cattle and sheep in the United States, may expand. If disease-carrying insects increase their winter survival and reproduce year-round in more States, the geographical distribution of blue tongue, which is caused by a virus, may expand northward and eastward. Anaplasmosis, a rickettsial infection of ruminants, is the second most important disease of cattle in the United States. The distribution of the habitat of the insect carrier of the disease could expand to northern States with climate change, and the day-to-day activity of the insects may increase, also causing an increase in disease transmission.

The horn fly causes annual losses of $730.3 million in the beef and dairy cattle industries (Drummond, 1987). Schmidtmann and Miller found that with the very warm GFDL climate change scenario, the horn fly season throughout most of the United States was extended by 8 to 10 weeks, horn fly populations increased (see Figure 10-11), and the average daily gain in beef cattle decreased. This horn fly increase will cause substantially greater reductions in the average daily gain of growing beef cattle. The GFDL simulation also increased pest activity in dairy cattle in the northern and northwestern States, a result that could significantly decrease milk production. Conversely, the summertime activity of the horn fly decreased in the southern States because the warmer climate exceeded the horn fly's tolerance to high temperatures.

Limitations

Horn fly data are based on counts taken at various times, under varying weather and management conditions. However, the prediction of current horn fly populations appears to be well correlated with observations. The model is not validated for the high temperatures predicted for the climate change. Schmidtmann and Miller used only the hottest scenario, GFDL; the other scenarios may have resulted in less of a geographic shift in the range of the horn fly.

It should be noted that this analysis is based on current livestock management breeds and distribution. Possible changes in these factors are beyond the scope of this study.

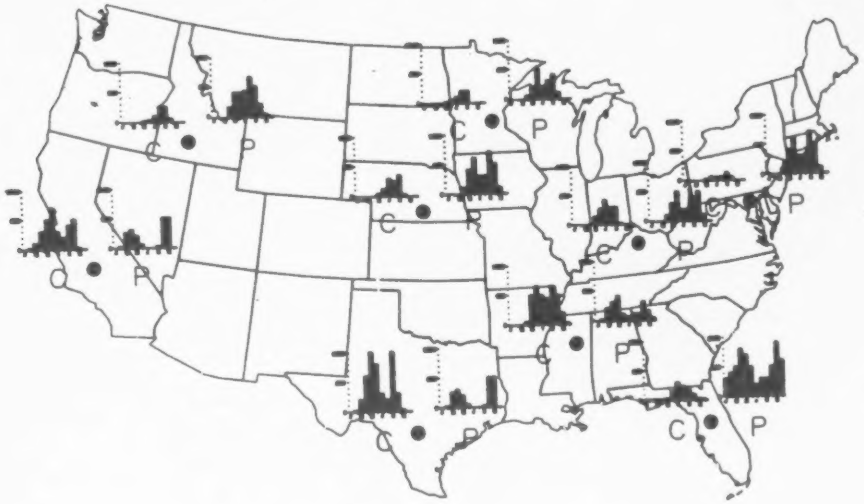

C
P
C
P
C
P
C
P
C
P
C
P
C
P
C
P
C
P

Figure 10-11. Current (C) and projected (P) populations of the horn fly, a major pest of beef and dairy cattle, using the GFDL climate change scenario.

Source: Schmidtmann and Miller, Volume _.

Implications of Livestock Studies

With climate change, patterns of livestock diseases and pests may change. Tropical livestock diseases may become more of a threat, because more geographical areas are potential ranges for the insect carriers of the diseases. Temperature conditions may improve in the winter but may be exacerbated in the summer. Reproductive capabilities may be lower.

ECONOMIC AND ECOLOGICAL IMPLICATIONS

Even though the U.S. agricultural system has historically shown considerable resiliency and may be less vulnerable to climate change than unmanaged ecosystems, many reasons to avoid complacency concerning the predicted climate change remain. While the studies summarized in this chapter show that the U.S. supply of basic commodities probably is not threatened by climate change, food prices may increase for consumers, and agricultural exports may be significantly reduced.

Costs of Adjustments

Since our agricultural production system consists mostly of specialized farms producing commodities in geographically specialized patterns of production, the costs of adjustments to changes in comparative advantage among agricultural regions with ensuing changes in resource use and agricultural infrastructure may be quite high. These shifts will also entail involvement of and costs to the Federal Government.

Effects of CO_2

It is also important to note that the crop modeling studies showed that the direct effects of CO_2 on crop photosynthesis and water-use efficiency ameliorate the negative effects of climate change in some locations but not uniformly and not everywhere. While much work remains to be done to improve both climate and crop models, reliance on overly optimistic assessments about the beneficial effects of CO_2 must be avoided when policy options are considered.

Water Quality

Changes in the agricultural production system are likely to have significant impacts on resource use and the environment. Many of the agricultural studies suggest that climate warming could result in changes in water quality from agricultural chemicals, increases in pesticide usage to control changes in pest vectors, and accelerated rates of demand for water for irrigation. Climate change could thus exacerbate many of the current trends in environmental pollution and resource use associated with agriculture as well as initiate new ones.

A northward migration of agriculture will increase the use of irrigation and fertilizers on sandy soils, thus endangering underlying groundwater quality. From South Dakota to southern Canada, critical prairie wetlands may be lost to drainage and conversion to cropland. Many of these areas are important wildlife habitats. Shifts in agricultural activities may increase the susceptibility of soils to wind and water erosion.

Global Agriculture

Finally, U.S. agriculture is an integral part of the global, international agricultural system. Consequently, the adjustment of U.S. agriculture to climate change cannot be considered in isolation from the rest of the world. The optimal configuration of U.S. adjustments will depend very much on how simultaneous changes in regional climate affect global agriculture and how other countries, in turn, respond to those changes.

NATIONAL POLICY IMPLICATIONS

Since climate change appears likely to reconfigure the agricultural activities and demographics of rural America, policies are needed to ease the inevitable adjustments and ensure the sustainability of our natural and human resources (see Schuh and Dudek, Volume _). Following are specific policy areas that policymakers could investigate to respond appropriately to the projected climate change.

Commodity Policies

Agricultural pricing and production policies should promote efficient adjustment to the changing conditions of global supply and demand induced by the greenhouse effect, which may include shifts in comparative advantage among regions and increased likelihood of droughts in some regions. Although these shifts may be slow, the cumulative effects are large and they deserve close monitoring. Market forces as well as government programs will play a crucial role in creating the flexibility to respond to climate changes by sending signals on the efficient use of resources, and in mitigating their ultimate impact as they have done in the past. Agricultural policies should be evaluated to ensure that they are appropriate to both current and future conditions.

Land-Use Programs

Federal legislation aimed at reducing the use of newly plowed grasslands, e.g., the "Sod-Buster Bill," and the related "Swamp-Buster Bill," which restricts agricultural encroachment into wetlands subject to flooding and water-logging, are examples of new policies meant to protect marginal lands. The basic goals of these new laws, which are part of the 1985 Farm Bill, are to protect the most erodible farmland by removing it from crop production and to use conservation as a tool for reducing overproduction.

Another program established in the 1985 Farm Bill that may help alleviate the negative effects of climate change is the Conservation Reserve Program. This program is aimed at removing from crop production the cropland classified as "highly erodible" by the Soil Conservation Service. The bill created a new form of long-term contract of up to 10 years and provides payments to farmers who apply conservation practices, such as maintaining a grass cover, on those acres. If successful, the Conservation Reserve Program may reduce the impact of climate fluctuations on total grain production by taking the most sensitive lands out of use.

The 1988 drought, however, demonstrates that the Conservation Reserve Program may be difficult to maintain in the face of climate stress. As the drought worsened during the summer, use of the set-aside lands was requested so that badly hit farmers could salvage some economic benefits from these acres. Such conflicts may be more common in the future, and land retirement strategies must be weighed against possible needed increases in production in the future.

Awareness of potential changes in agricultural land use due to regional climate change should be built into land-use planning programs, especially in regions where agricultural activities may expand into natural, unmanaged ecosystems. Large-scale drainage and water projects would need environmental impact studies to carefully assess this potential expansion of agricultural land (see Baldwin, Volume _).

Water-Resource Management Programs

Current water supply policies do not generally encourage optimum water-use efficiency. A greater degree of water efficiency should promote flexibility in light of the potential for increased irrigation demands with climate change. Policies such as water transfers and markets should be evaluated for irrigated areas.

Water Quality Policy

The increased use of agricultural chemicals, and changes in the hydrological cycle, threaten both soil and water supplies, and eventually, public health. These effects could be ameliorated by including potential climate change effects in water quality planning and by supporting alternative pest management strategies that use such techniques as biological control, genetic resistance, and innovative cropping systems.

Risk Management

Changes in the frequency, intensity, and location of extreme events are important for agriculture and the regional income that it produces. The adequacy of the private crop insurance and Federal disaster payment programs should be assessed in the face of climatic uncertainty. For example, only about 20-25% of potentially insurable acreage is currently covered by crop insurance. Farmers tend to rely on Federal disaster relief programs to bail them out of such disasters as droughts, floods, hail, and windstorms. Financial risk is also part of the credit structure that covers land, equipment, and production in modern farming.

The frequency and magnitude of climate extremes may be altered with climate change. Responding to the changes may be costly for the government if crops fail frequently. The Drought Relief Bill for the drought of 1988 is scheduled to cost $3.9 billion to cover just 1 year of a climatic extreme. On the other hand, some areas that currently suffer from climate extremes may benefit from climate change. Risk policy mechanisms for relief, recovery, and mitigation of climate change should be examined so that they will be ready to help farmers adjust.

International Trade Agreements

Policies designed to ease the adjustment to greenhouse effects must be global in scope because the effects, although varied, are global in nature. Comparative advantage will shift significantly both within the United States and in other countries. Population and economic activities also will change geographically with climate change, thus affecting the location of demand for agricultural products. It is already a goal of U.S. agricultural policy to incorporate global conditions of supply and demand into the agricultural sector. The potential seriousness of the impacts on the agricultural production system of the greenhouse effect may provide added incentive to establish such policies both nationally and globally. The vulnerability of current and potential food-deficit regions to climate change should also be considered.

Agricultural Contributions to the Greenhouse Effect

Agriculture itself is an active contributor to the greenhouse effect. Clearing of forested land for agriculture often involves burning of trees and shrubs that release CO_2. The biomass that is not burned tends to decay gradually, also emitting CO_2. Agricultural activities release other radiatively active trace gases. Flooded rice fields emit methane (CH_4) as a product of the anaerobic decomposition of organic matter. Ruminants also release methane as a consequence of their digestive processes. In addition, soils may volatilize some of the nitrogenous fertilizer applied to them in the form of nitrous oxide (N_2O). Finding effective ways to reduce these emissions presents a major challenge to the agricultural research community. In this regard, the Conservation Reserve Program and forestation efforts could provide a partial solution, since vegetation fixes CO_2 from the air.

Agricultural Research

The agricultural research community should enhance climate change research from the field level to the national policy level. It should continue to breed heat- and drought-resistant crop varieties and new crop species in preparation for global warming. Research in biotechnology may also be directed toward alleviating the negative effects of climate change. Improved water use and irrigation efficiency also take on renewed importance in the light of potential climate change.

Reduction of agricultural emissions of trace gases also deserves research attention. Development of nitrogen-fixing corn would help decrease fertilizer applications and thus agricultural emissions of N_2O. This would also mean a significant improvement in groundwater contamination.

RECOMMENDATIONS FOR FURTHER RESEARCH

1. Crop productivity -- Study the interactive effects of climate variability and change, CO_2, tropospheric ozone, UV-B from stratospheric ozone depletion, and other environmental and societal variables on agricultural productivity.

   Because of the significant changes in production indicated by these studies, the need for better simulation of the direct effects of CO_2 in the crop models, and the limited adjustment studies performed, further research should be conducted on a longer term basis. Necessary work includes validation of the crop models, resolving the differences in forecasts of the GCMs, and designing more appropriate scenarios including changes in climatic variability. Physiologically based submodels are needed for the effects of increased CO_2 on various crops. The effects on cotton also should be studied because cotton is a major crop, and because daylength may not allow it to shift northward. All the crop models should be improved in their simulation of the effects of increasing temperatures.

Research to this point has provided windows of knowledge concerning certain crops (especially soybeans) at specific stages of their life cycles. Both the direct and the climate change effects of high CO_2 are probably quite different at different stages of development. Research should be performed on the interactive effects of CO_2 and temperature over the whole life cycle of the plant, with realistic conditions of water and nutrition, rather than with "pampered" plants under optimal conditions. Then crop response to the combined climatic and physiological effects of CO_2 may be predicted more realistically.

2. Adaptation strategies -- The dynamic nature of climate change also needs to be studied: What is the rate of adaptation of regional agricultural systems compared to the rate of climate change? Evaluation of the thresholds of sensitivity of U.S. agriculture is needed. Studies should analyze the ability of various aspects of the agricultural production systems to adapt to various rates and degrees of climate change to determine these thresholds of sensitivity.

3. Agricultural economics -- Expand the national analysis to include crops and regions not now included (for example, cotton and grasslands, and pasture in the western regions of the United States). Conduct further analyses of regional implications of shifts in agriculture.

4. International agriculture -- Study the potential shifts in international comparative advantage and the vulnerability of food-deficit regions, and evaluate the implications of such shifts for the United States.

5. Environmental impacts -- Elucidate the impacts of climate change on water quantity, water quality, and other components of the environment caused by shifts in crop and livestock production and related industries.

REFERENCES

Acock, B., and L.H. Allen Jr. 1985. Crop respones to elevated carbon dioxide concentrations. In: Strain, B.R., and J.D. Cure, eds. Direct Effects of Increasing Carbon Dioxide on Vegetation. Washington, DC: U.S. Department of Energy. DOE/ER-0238. pp. 33-97.

Adams, R.M., S.A. Hamilton, and B.A. McCarl. 1984. The Economic Effects of Ozone on Agriculture. Corvallis, OR: U.S. Environmental Protection Agency. EPA-600/3-84-090.

Ames, David R. 1981. Effect of climate on livestock production data. In: Knapp, F.W., ed. Systems Approach to Animal Health and Production. Lexington, KY: University of Kentucky, pp. 148-148.

Callaway, J.M., F.J. Cronin, J.W. Currie, and J. Tawil. 1982. An analysis of methods and models for assessing the direct and indirect impacts of CO_2-induced environmental changes in the agricultural sector of the U.S. economy. Richland, WA: Pacific Northwest Laboratory, Battelle Memorial Institute. PNL-4384.

Carbon Dioxide Assessment Committee. 1983. Changing Climate. Washington, DC: National Academy of Sciences.

Carsel, R.F., C.N. Smith, L.A. Mulkey, J.D. Dean, and P. Jowise. 1984. Users Manual for the Pesticide Root Zone Model (PRZM). Athens, GA: U.S. Environmental Protection Agency. EPA-600/3-84-109.

Council for Agricultural Science and Technology. 1984. Long-Term Viability of U.S. Agriculture. Aces, Iowa. Report No. 114.

Cure, J.D. 1985. Carbon dioxide doubling responses: a crop survey. In: Strain, B.R., and J.D. Cure, eds. Direct Effects of Increasing Carbon Dioxide on Vegetation. Washington, DC: U.S. Department of Energy. DOE/ER-0238. pp. 99-116.

Decker, W.L., V. Jones, and R. Achutuni. 1985. The impact of CO_2-induced climate change on U.S. agriculture. In: White, M.R., ed. Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Ficheries, Forests and Human Health. Washington, DC: U.S. Department of Energy. DOE/ER-0236. pp. 69-93.

Doorenbos, J., and A.H. Kassam. 1979. Yield Response to Water. Rome: Food and Agriculture Organization of the United States. FAO Irrigation and Drainage Paper 33.

Drummond, R.O. 1987. Economic aspects of ectoparasites of cattle in North America. In: Leaning, W.H.D., and J. Guerrero, eds. Proceedings of the MSD AGVET Symposium, The Economic Impact of Parasitism in Cattle. XXIII. World Veterinary Congress. Montreal, Quebec. pp. 9-24.

Hansen, J., I. Fung, A. Lacis, D. Rind, G. Russell, S. Lebedeff, R. Ruedy, and P. Stone. 1988. Global climate changes as forecast by the GISS 3-D model. Journal of Geophysical Research (In press.)

Horner, G., L. Putler, and S.E. Garifo. 1985. The Role of Irrigated Agriculture in a Changing Export Market. Washington, DC: U.S. Department of Agriculture, Economic Research Service. ERS Staff Report AGES850328.

Jones, J.W., K.J. Boote, S.S. Jagtap, G. Hoogenboom, and G.G. Wilkerson. 1988. SOYGRO V5.41: Soybean Crop Growth Simulation Model. User's Guide. Florida Agr. Exp. Sta. Journal No. 8304, IFAS. Gainesville: University of Florida.

Jones, J.W., J.W. Mishoe, G.Wilkerson, J.L. Stimac, and W.G. Boggess. 1986. Integration of soybean crop and pest models. In: Frisbie, P.E., and P. Adisson, eds. Integrated Pest Management on Major Agriculture Systems. Texas Agriculture Experiment Station. Publication No. MP-1616.

Kimball, B.A. 1985. Adaptation of vegetation and management practices to a higher carbon dioxide world. In: Strain, B.R., and J.D. Cure, eds. Direct Effects of Increasing Carbon Dioxide on Vegetation. Washington, DC: U.S. Department of Energy. DOE/ER-0238. pp. 185-204.

Land Evaluation Group. 1987. Implications of climatic warming for Canada's comparative position in agricultural production and trade. University School of Rural Planning and Development. University of Guelph. Guelph, Ontario.

Monteith, J.L. 1965. Radiation and crops. Experimental Agricultural Review 1(4):241-251.

New York Times. August 12, 1988. Drought cutting U.S. grain crop 31% this year, by K. Schneider. p. A1.

Parry, M.L., T.R. Carter, N.T. Konijn, eds. 1988. The Impact of Climatic Variations on Agriculture. Vol. 1. Assessments in Cool Temperate and Cold Regions. Kluwer, Dordrecht.

Postel, S. 1986. Altering the Earth's Chemistry: Assessing the Risks. Worldwatch Paper 71. Washington, DC: Worldwatch Institute.

Chapter 10

Ritchie, J.T., and S. Otter. 1985. Description and performance of CERES-Wheat: A user-oriented wheat yield model. In: Willis, W.O., ed. ARS Wheat Yield Project. Washington, DC: U.S. Department of Agriculture, Agricultural Research Service. ARS-38. pp. 159-175.

USDA. 1987. U.S. Department of Agriculture. Agricultural Statistics. Washington, DC: U.S. Government Printing Office.

Warrick, R.A., R.M. Gifford, M.L. Parry. 1986. CO_2, climatic change and agriculture. Assessing the response of food crops to the direct effects of increased CO_2 and climatic change. In: Bolin, B., B.R. Doos, J. Jager, and R.A. Warrick, eds. The Greenhouse Effect, Climatic Change and Ecosystems. A Synthesis of the Present Knowledge, SCOPE 29. New York: John Wiley and Sons, pp. 393-473.

Webster, A.J.F. 1981. Weather and infectious disease in cattle. The Veterinary Record 108:183-187.

World Bank. 1988. World Population Projections. 1987-1988 edition. Short- and Long-term Estimates. Zachariah, K.C., and Vu, M.T. Baltimore, MD: Johns Hopkins University Press.

World Food Institute. 1987. World Food Trade and U.S. Agriculture, 1960-1986. Aces, IA: Iowa State University.

CHAPTER THIRTEEN

GLOBAL CLIMATE CHANGE HOLDS PROBLEMS AND UNCERTAINTIES FOR AGRICULTURE

NORMAN J. ROSENBERG

INTRODUCTION

The planet earth may already be committed to a degree of climate change that will have considerable impact on agriculture. It is difficult to state with assurance, however, just what the impacts will be since, despite some certainties or near certainties with respect to aspects of the climate change question, there remains a good deal that is unknown or unknowable at this time.

There is a widely held consensus among climatologists that the increasing concentration of carbon dioxide and other trace gases in the atmosphere must, of necessity, lead to a global warming in the lower layers of the atmosphere through the so-called "greenhouse effect." Until recently climatologists have been concerned primarily with carbon dioxide, which had increased from its preindustrial concentration of about 280 parts per million by volume (ppmv) to about 345 ppmv in 1986. However, a few years ago it became evident that other "greenhouse" gases—methane and nitrous oxide, both produced by industrial and natural processes, and the chlorofluorocarbons (CFCs), a group of manufactured gases used for refrigeration, manufacture of lightweight plastics such as styrofoam, and other purposes—were increasing still more rapidly. If current trends continue for the next fifty years, the mean global temperature increase caused by all of these gases could be about 3.5°C, with a 9 in 10 chance that the change will fall within a range of 1.5 to 5.5°C. Global mean temperature is now about as high as it has been anytime since the end of the last glaciation about 18,000 years ago. The predicted greenhouse warming would create a climatic environment totally beyond the experience of civilized man.

It is also widely held that the warming will not be uniformly distributed but that the tropics will warm least. Warming is expected to increase progressively toward the polar regions, which may warm by as much as 10°C. Accordingly, the temperature difference between the tropics and the poles will decrease, and a general alteration of global weather systems and hence of climate--the integration of all weather events—will necessarily occur. However, the "state-of-the-art" is insufficiently advanced to give us a high degree of confidence about climatic changes that will occur on the regional and local scales, particularly with respect to precipitation. This matter is addressed in greater detail below.

In attempting to assess the implications for agriculture of prospective climatic changes we must recognize that agriculture is not a monolith or an industry that can be treated as fixed in its methods or even in the space that it occupies. For example, over the course of the last thirty or forty years, sorghum has been gradually displacing corn in northeastern Kansas and southeastern Nebraska at the same time that soybeans have been displacing corn at the margins of the traditional corn belt as far west as central Nebraska. These changes in land use typically occur in response to economic forces, technological changes, and climatic trends, the latter real or perceived. One cannot and should not attempt to predict what a climate change, either abrupt or gradual, will do to an agriculture fifty or seventy-five years from now by superimposing these changed climatic conditions upon agriculture as it is today. This, however, is what analysts, for lack of the appropriate techniques, have tended to do. (The development of such needed methodology is one of the objectives of RFF's newly formed Climate Resources Program.)

Yet there are some interpretations possible at this stage. Let us begin with what is probably quite obvious to all—that agriculture is an industry extremely sensitive to weather and climate—particularly when conditions deviate significantly from the normal for the season. Other industries are also weather-sensitive—tourism, for example. But while a sharp freeze in late spring can eliminate a season's growth of wheat, it will merely discommode the tourist briefly.

SENSITIVITY OF AGRICULTURE TO CLIMATIC STRESSES

There has been a general increase in the productivity of U.S. agriculture since the beginning of this century. The greatest increases have come about since the end of World War II as a result of advances in plant breeding, mechanization, and the use of fertilizers and chemical pesticides. This trend is illustrated for wheat yields in the Great Plains in figures 13-1a and 13-1b. Figure 13-1a (top) shows the period from 1925 to roughly 1970; figure 13-1b (bottom) carries the trend through 1985. Two very important facts can be drawn from figure 13-1: first, that the trend of rising wheat yields, experienced over almost forty years, flattened out in the beginning of the 1970s, although it appears to have risen somewhat in the first half of the 1980s; second, that sharply downward deviations from the overall upward trend occurred during the drought period of the 1930s.

The drought of the 1950s was concentrated in the southern Plains and portions of the Southwest. Yields declined, but the effect on average Great Plains wheat yields was less severe than in the 1930s. A strongly downward turn in wheat yields also occurred in the mid-1970s, another period of drought in the principal wheat-growing region of the country. While drought

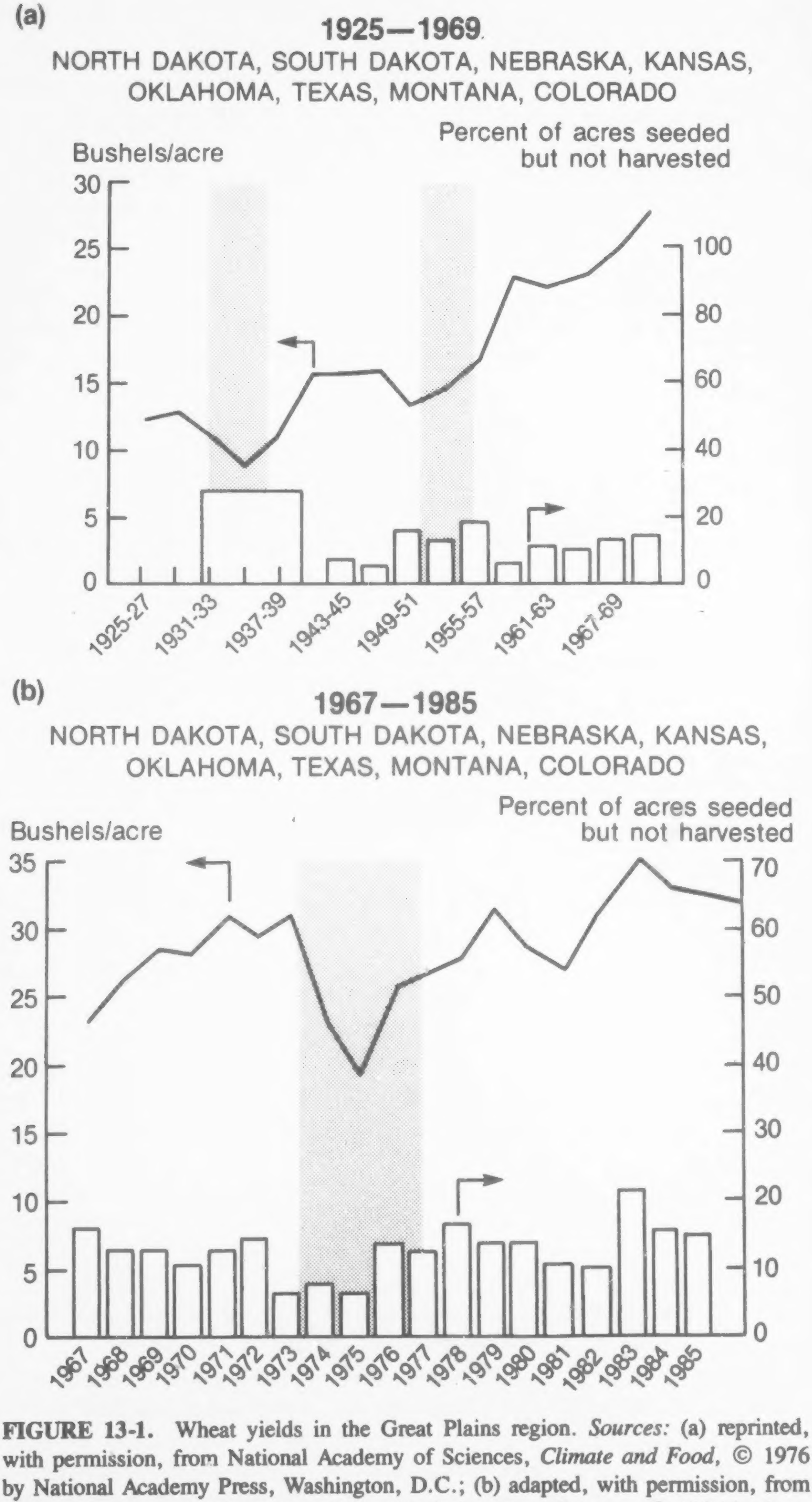


FIGURE 13-1. Wheat yields in the Great Plains region. *Sources:* (a) reprinted, with permission, from National Academy of Sciences, *Climate and Food,* © 1976 by National Academy Press, Washington, D.C.; (b) adapted, with permission, from C. Ford Runge, ed., *The Future of the North American Granary,* © 1986 by Iowa State University Press, Ames.

did lower yields in the Dakotas in 1985, the overall trend of the last few years has been upward because of the development of rust-resistant and semidwarf varieties and, most importantly, perhaps, because farm program compliance has led to the removal of poorer lands from production.

The sensitivity of wheat yields to weather conditions during the period 1973 through 1976 is particularly interesting. Droughts in the Great Plains during the 1970s were generally much less severe and shorter than in the 1930s and 1950s. A careful review of what actually happened to wheat production in the Great Plains in the mid-1970s is instructive. The 1974 crop was seeded under good moisture conditions. However, extreme dryness and heat during early summer, and to some extent hail, lowered yields sharply. The 1975 crop was hurt by the dryness of the seedbed at planting time. Stands were spotty and, despite fair rains during the spring, yields were the lowest of the decade. The 1976 crop was also seeded under very dry conditions. Snow cover was very poor during the winter period of what has been termed "the drought of the 1970s." Rains in spring were ample but the crop matured under hot dry conditions.

Thus, it appears that despite technology (cultivars, fertilizers, chemicals, mechanization) far more sophisticated than that of the 1930s, drought and moisture stress of even short duration reduced wheat production in the Great Plains quite severely. An important lesson to be learned from these figures is that our food-producing systems remain vulnerable to even relatively moderate climatic stresses. How much more vulnerable could we be if climate changes during the coming decades to the degree that many specialists now consider possible?

There are trends in U.S. agriculture that could also increase the vulnerability of our crops to a climatic change. Take the case of irrigation development in much of the Great Plains which depends upon the extraction of groundwater from water-bearing strata. Where these aquifers are only slowly rechargeable, as is the case for much of the Ogallala aquifer that covers portions of the states of Nebraska, Wyoming, Colorado, Kansas, Texas, and New Mexico, the development of irrigation provides only a temporary shelter against the impacts of drought. Costly agricultural systems have been put in place over much of the Ogallala. Water levels have fallen, increasing pumping costs considerably. As this process continues to the point that pumping costs are no longer economic, a return to rain-fed agriculture will necessarily occur. By then, however, the water that might have provided a strategic source for limited irrigation, animal watering, and other needs in time of drought will be much more difficult to pump and to pay for.

This bleak scenario is subject to change, however. Substantial improvements in the efficiency with which water is applied to the land, strategic irrigation only at critical stages of crop development, and other technological improvements already being introduced can greatly extend the useful life of the aquifer. Rising pumping costs should provide strong motivation for irrigators in this region to improve the efficiency with which they use this precious water resource.

Another disturbing trend is illustrated in figure 13-2 (from Kessler and coauthors, 1978). This is a satellite view showing vast dust storms originating in eastern Colorado and in western Texas during the winter of 1977. In west Texas, farming systems leave large areas of land uncovered in winter, exposing soils to severe wind erosion. A rush to increase acreage in grain crops, especially at the western margins of the Great Plains, stimulated by government policy in the early 1970s, reopened large areas of marginal soils that had been retired from cultivation after the earlier droughts in this century. When drought struck in the mid-1970s, dust began to blow off these lands again. With the conservation provisions of the Food Security Act of 1985, the federal government is now encouraging landholders to place some of this vulnerable land in the conservation reserve and through "sodbuster" provisions of the bill is discouraging farmers from converting land now in pasture or range to crops.

Yet another trend that may be increasing agricultural vulnerability to climatic stress is the decreasing size of the gene pool from which most modern varieties of our grain crops are drawn. Vast areas of the United States are planted to corn hybrids that are derived from a very limited number of parents (Evans, 1985). Further, the mechanization of agriculture now makes it possible for vast areas of the United States to be planted within just a few weeks' time. Hence, there is a uniformity of genetic material and a synchro-

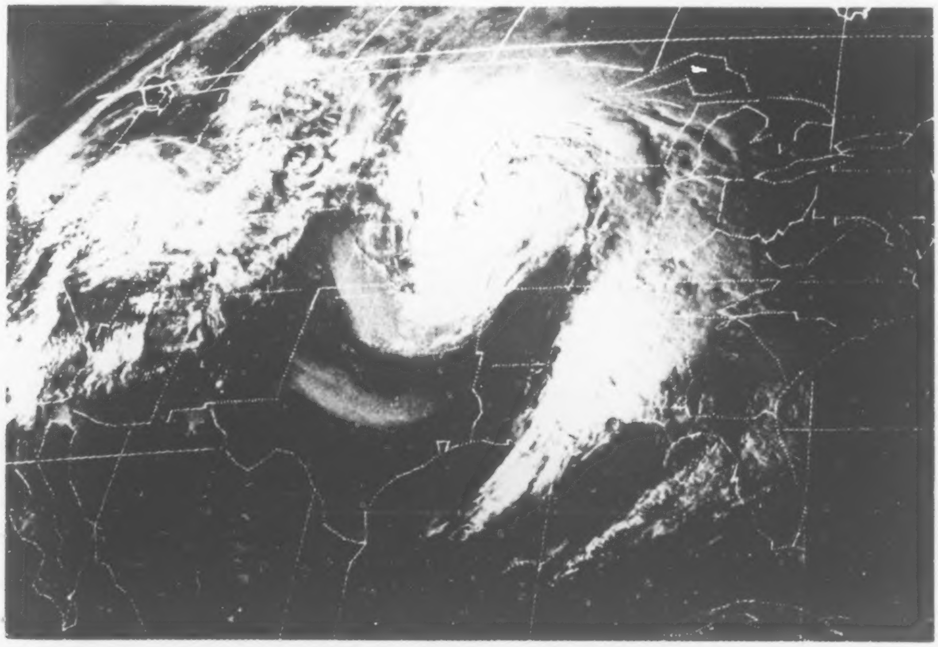


FIGURE 13-2. GOES satellite picture, February 23, 1977, showing separate dust storms originating in eastern Colorado and the Panhandle region of Texas. According to Kessler and coauthors (1978), the origin of the Panhandle dust storm coincides very closely with an abrupt change in agricultural practice. Rangeland is predominant on the New Mexico side of the border and cropland on the Texas side.

nization of plant growth and development in this nation that makes U.S. crops more vulnerable to damage by large-scale weather systems. In previous years, the greater diversity and greater variation in planting and maturity times provided a degree of insurance or "hedging," so that the overall response of the U.S. agricultural system to stressful weather was less severe. This should not be taken to mean that general productivity is declining. In fact the opposite is true. Although our cereal crops yield considerably better than before, there is evidence that cereal production fluctuates in absolute terms more widely now than previously in response to effects caused by technology, economic, and weather factors.

CLIMATIC CHANGE AND PROSPECTS FOR AGRICULTURE

Agriculture, despite (or, in some cases, because of) technological developments, remains very vulnerable to the effects of climatic stress—drought, frost, hail, excessive heat, and so forth. But, how will specific climatic changes of the sort anticipated in coming decades affect agriculture? As pointed out above, a general warming of the lower atmosphere is expected to occur as the atmosphere becomes further enriched in carbon dioxide and other radiatively active trace gases. The reduction in temperature gradient between the tropics and the high latitudes will cause significant alterations in weather systems throughout the world. Further, a warming of the atmosphere means, per se, an intensification of the hydrologic cycle. In global terms, more water will be evaporated because of the higher temperatures, and there will be more precipitation. But where precipitation will be increased and where decreased is much less certain at this time than is the notion of general global warming and latitudinal differences in the distribution of that warming.

Figures 13-3a, 13-3b, and 13-3c have been redrawn from a chapter by Schlesinger and Mitchell in the Department of Energy's 1985 state-of-the-art review of the carbon dioxide issue. These figures illustrate the projections of three groups of global climate modelers of changes in climate (temperature, precipitation, and soil moisture) that could follow an increase in all of the radiatively active ("greenhouse") trace gases equivalent in effect to a doubling of the global atmospheric CO_2 concentration over that of preindustrial times. These figures have been redrawn for simplicity to show only Africa and North America in June, July, and August. Changes predicted by the models of the Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute of Space Studies (GISS), and National Center for Atmospheric Research (NCAR) are shown in the figures.

Predictions of temperature increases in the middle of North America range from 2° to 8°C, depending on model. Projections for precipitation change in this region during June, July, and August range from -1 to $+1$ millimeter per day (mm/day). This implies an increase or decrease of about 32 percent of the current mean of 287 mm (11.3 in.) in Lincoln, Nebraska, in summer.

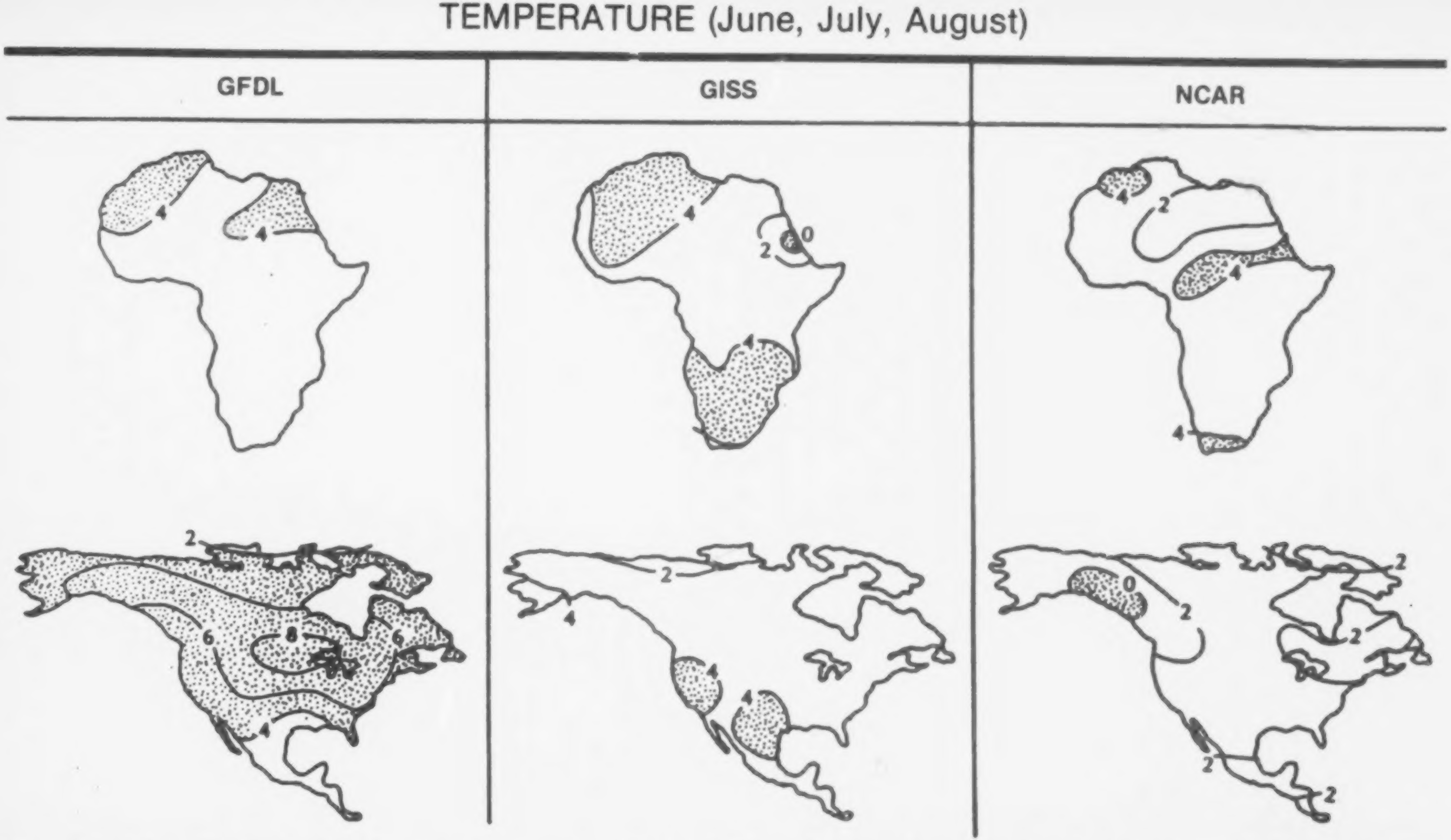

TEMPERATURE (June, July, August)
GFDL
GISS
NCAR
4
4
2
6
8
6
6
4
4
0
2
4
2
4
4
4
4
2
4
4
2
0
2
2
2
2
2

FIGURE 13-3a. The distribution of surface air temperature change (°C) for a doubling of atmospheric carbon dioxide concentration for June, July, and August simulated by the global climatic models of GFDL (left), GISS (center), and NCAR (right). Stipple indicates temperature increases greater than 4°C. (Adapted from figure 4.39 of Schlesinger and Mitchell, 1985.)

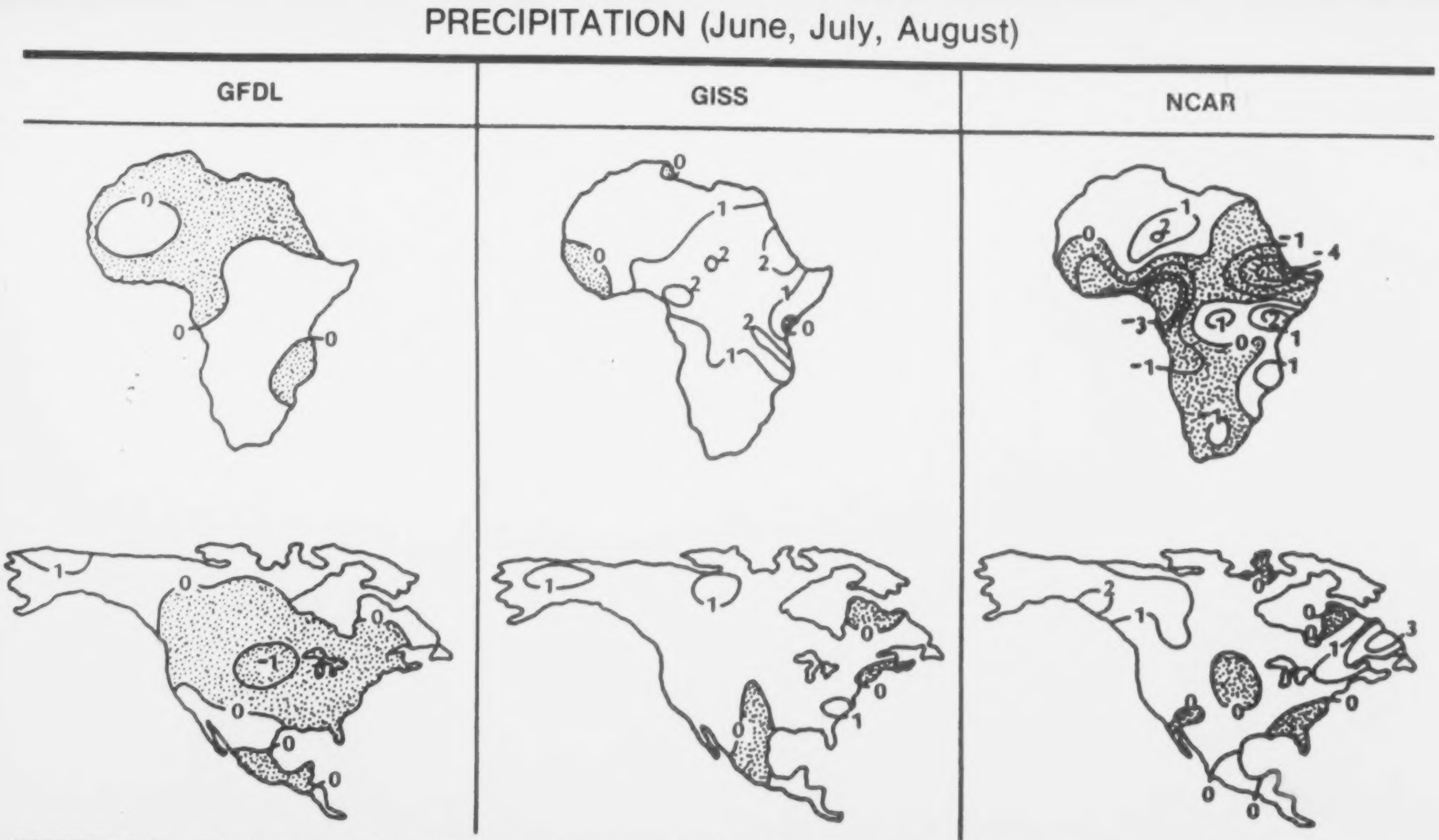

PRECIPITATION (June, July, August)
GFDL
GISS
NCAR

FIGURE 13-3b. The distribution of precipitation rate change (mm/day) for a doubling of atmospheric carbon dioxide concentration for June, July, and August simulated by the global climatic models of GFDL (left), GISS (center), and NCAR (right). Stipple indicates a decrease in precipitation rate. (Adapted from figure 4.42 of Schlesinger and Mitchell, 1985.)

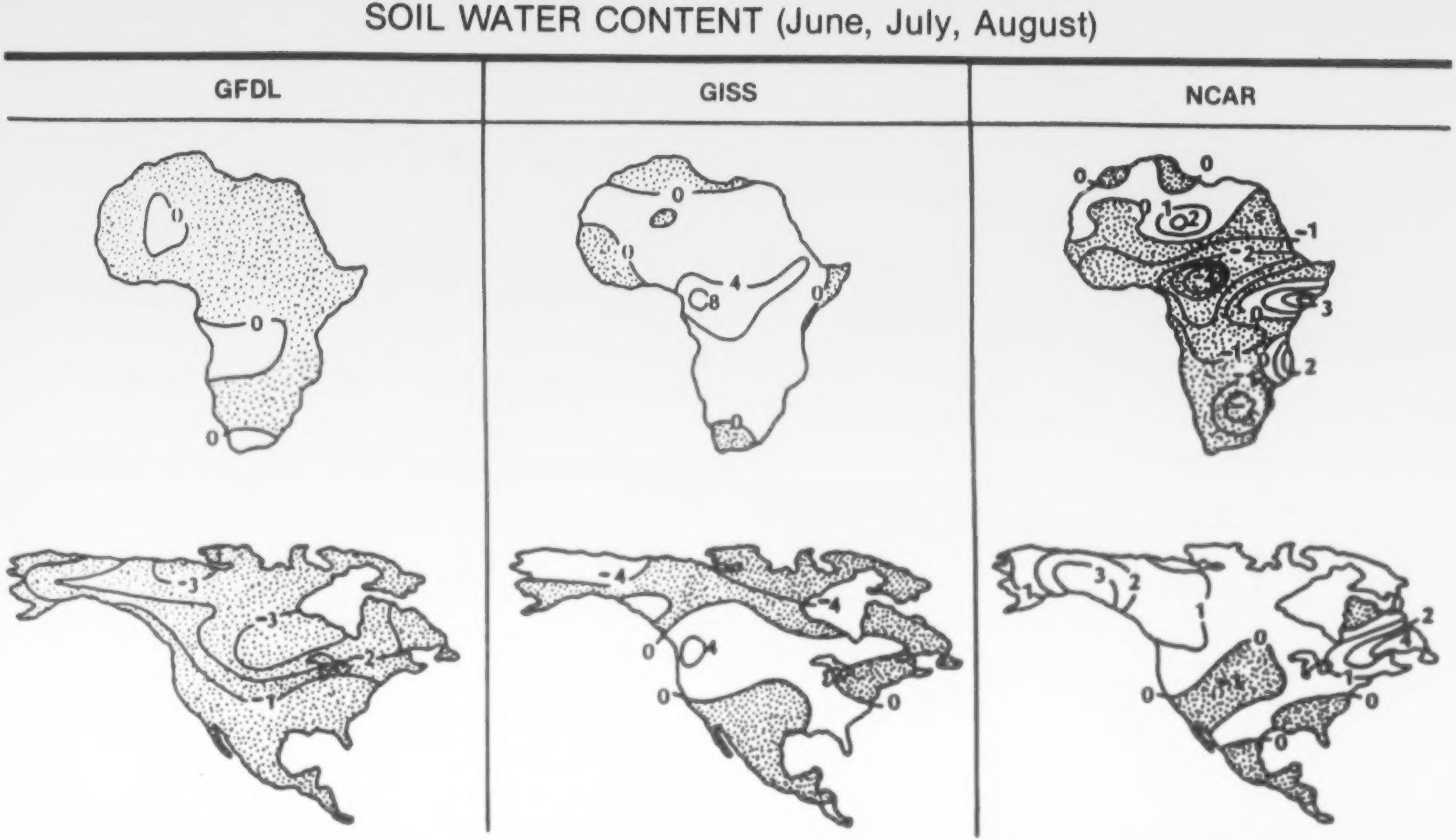

SOIL WATER CONTENT (June, July, August)
GFDL
GISS
NCAR
0
-1
-2
-3
-4
1
2
3
4
8

FIGURE 13-3c. The distribution of soil water change (cm) for a doubling of atmospheric carbon dioxide concentration for June, July, and August simulated by the global climatic models of GFDL (left), GISS (center), and NCAR (right). Stipple indicates a decrease in soil water. (Adapted from figure 4.45 cf Schlesinger and Mitchell, 1985.)

In Durango, Colorado, this change would mean an increase or decrease of 68 percent of the current mean of 135 mm (5.31 in.). In West Africa precipitation changes range from −1 to +2 mm/day.

Perhaps most critical, however, are the predictions of changes in soil water balance that follow from the predicted changes in precipitation and evaporation. GFDL predicts a soil water deficit of as much as 30 mm for the summer season in North America; GISS predicts no change there, while NCAR predicts from 0 to 10 mm reduction in soil water. In West Africa the predictions differ widely as well.

Aside from these generally large differences in the prediction of temperature, precipitation, and soil water balance for the year as a whole, the GFDL, GISS, and NCAR models also predict quite different seasonal patterns of climatic change. However, all three models do show a moistening of the soil from northern Mexico to the latitude of Sitka, Alaska, from October to April. GFDL predicts a drying everywhere from April to September, GISS predicts late summer drying south of the U.S.-Canada border, and NCAR predicts some moistening north of the Mexican border throughout the year.

Obviously, then, the state of the art in global climatic modeling circa 1985 was not yet sufficiently good to provide agreement as to precisely what will happen in a world where atmospheric CO_2 concentration is greatly increased and a significant greenhouse warming has occurred. Despite continuing improvements in global climate modeling, the detail needed for purposes of regional planning is still lacking.

These models are good enough at this point, however, to alert us to the likelihood of significant changes to come in the temperature regime, in the spatial and temporal distribution of precipitation, and in the seasonal availability of soil moisture. They are also sufficiently good to alert us to the possibility that CO_2 induced climate change could lead to more frequent, more severe, or more protracted droughts, somewhere on the planet. Regions now susceptible to serious drought are not, necessarily, the most likely to suffer, but it is the people living in these regions who are, in a sense, at greatest risk if that is what happens.

Additionally, the disagreement among the models leaves room for considerable doubt as to whether the state of the art is sufficiently good to allow us to predict with certainty that any one region of the United States or of the world will suffer or benefit from a specific degree and combination of climatic change. Where this leaves us in terms of preparing for what appears to be an almost inevitable climate change will be addressed below.

PLANT RESPONSES TO INCREASING ATMOSPHERIC CARBON DIOXIDE CONCENTRATIONS

The models leave us with considerable uncertainty regarding the regional distribution of climatic change and its possible consequences. We can, however, be somewhat more certain about some of the biological consequences, if the carbon dioxide concentration of the atmosphere continues to rise as predicted. Carbon dioxide is a necessary building block in photosynthesis, as is shown in equation 1.

$$\text{carbon dioxide} + \text{water} \xrightarrow[\text{chlorophyll}]{\text{light}} \text{carbohydrates} + \text{water} + \text{oxygen} \qquad (1)$$

It is a well-known and demonstrable fact that plants, when exposed to increased concentrations of carbon dioxide, respond (all other factors remaining unchanged) with an increased rate of photosynthesis. This increase in photosynthesis normally leads to larger and more vigorous plants and to higher yields of total dry matter (roots, shoots, leaves) and often of harvestable product as well. The behavior described here is demonstrated particularly by plants of the C_3 category which includes most of the world's small grains, legumes, root crops, cool season grasses, and trees. Another category of plants, the C_4 or tropical grasses such as corn, sorghum, millet, and sugar cane, are naturally more efficient photosynthesizers than are the C_3 plants. They too respond, but less markedly, to increases in atmospheric carbon dioxide. However, the C_4 plants show another interesting response to increased carbon dioxide in the atmosphere: their consumption of water by transpiration is reduced because of partial closure of the leaf stomata (pores) induced by high carbon dioxide concentration. This effect is also demonstrated by the C_3 plants. This reduction in transpiration is not accompanied by any significant loss in photosynthesis. Hence, the C_4 plants have a higher water use efficiency (production per unit of water consumed) in the presence of elevated levels of carbon dioxide because of reduced transpiration. The C_3 plants experience a still greater improvement in water use efficiency because of reduced transpiration and increased photosynthesis.

Thus, there will be benefits from the increasing concentration of carbon dioxide in the atmosphere—increased photosynthesis in many important species and decreased water consumption in most species. This direct "fertilization" effect of carbon dioxide should offset detrimental climatic changes to some degree. In cases where the climatic changes are clearly beneficial and increase the potential for production—for example, through increased warmth in the northern parts of the temperate zone or increased soil moisture in the semi-arid regions—the fertilization effect increases the likelihood that the greater production potential can be realized.

CAN AGRICULTURE ADJUST TO CHANGING CLIMATES?

This is a very difficult question to answer in view of the many uncertainties about the kinds and regional distributions of climatic changes in the offing. As shown above, agricultural production is, despite many technological advances, very sensitive and vulnerable to the stresses imposed by climate. It is important to recognize, however, that agricultural science has made it possible to overcome some of the limitations imposed by climate.

A case in point is illustrated in figure 13-4 (Rosenberg, 1982). The area in which hard red winter wheat is grown in the United States expanded greatly during the period 1920 to 1980. Hard red winter wheat now grows as far north as the southern Prairie provinces and as far south as central Texas. In the Northern Plains hard red winter wheat now competes with spring wheat.

Winter wheat has certain advantages. It is planted in fall and has a few months to become established before winter. Through winter the crop is dormant, beginning to grow again when spring arrives. The crop is harvested in early summer before the weather becomes very hot and, often, very dry. Finally, winter wheat is planted during the normally dry fall period, while the planting date for spring wheat is always uncertain since the soil must thaw and dry sufficiently before it can be planted.

Geographic expansion of the hard red winter wheat zone in North America, shown in figure 13-4, has occurred over a climatic gradient greater in many ways than the changes projected to follow from an equivalent doubling of the atmospheric carbon dioxide content. For example, the town of Sidney in Montana lies in the expansion zone of the hard red winter wheat crop. There the mean annual temperature is 4.2°C lower than in Sidney, Nebraska, where winter wheat has been grown since before 1920. Annual precipitation is 88 mm (3.46 in.) or 20 percent less and the growing season is ten days shorter at Sidney, Montana. Further, the difference between coldest and warmest month is 6.5°C greater at the Montana Sidney.

A study of the interaction between farmers and agricultural scientists and the interplay of economic forces and technological advances that made this crop migration possible could provide important insights as to how agriculture responds to changes in which climate is a factor. The case is also instructive because it involves change at the margins of a settled agricultural region with farms, agribusiness, service industries, and people who depend on these for their incomes. We expect that, as climate changes, it is the margins that will be first, and perhaps most, affected. The western edge of the Great Plains where moisture is the limiting factor, the northern edge of the corn belt where warmth is the limiting factor, and other such regions are those that should be studied most urgently.

CONCLUSIONS

In this writer's view, it is yet too early to encourage specific policies aimed at changing the face of American agriculture in preparation for climatic change. The nature and geographic distribution of the potential changes are still too uncertain to justify specific diversions of land from one use to another. Of course, sound, proven practices such as removing land from cultivation on the margins of the semi-arid zone should be encouraged. The implicit subsidies for mining groundwater in the Ogallala formation that encourage wasteful use of irreplaceable water should be discouraged. These

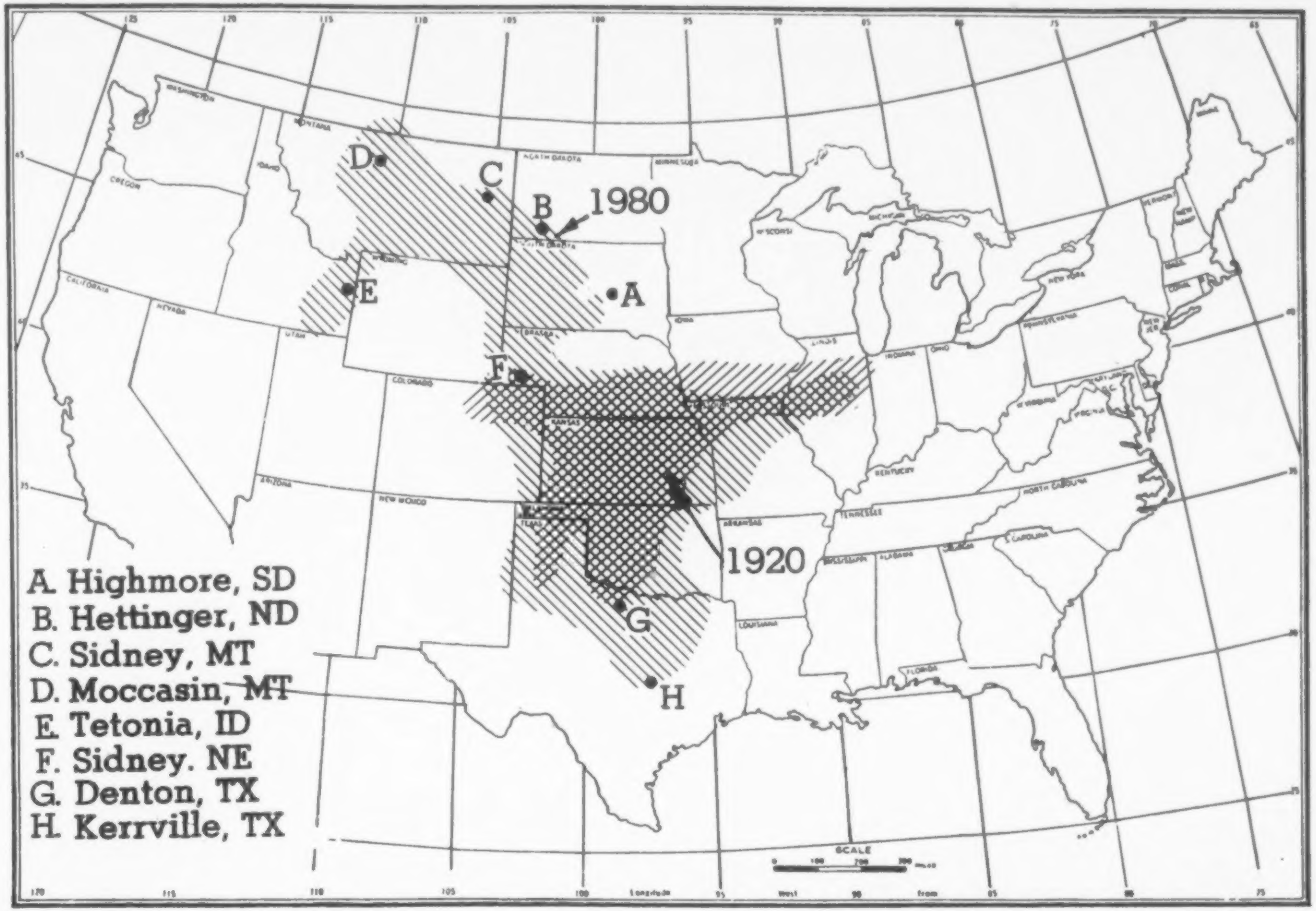

D
C
B
1980
A
E
F
1920
G
H
A. Highmore, SD
B. Hettinger, ND
C. Sidney, MT
D. Moccasin, MT
E. Tetonia, ID
F. Sidney. NE
G. Denton, TX
H. Kerrville, TX
SCALE

FIGURE 13-4. Extent of the hard red winter wheat zone in 1920 and 1980 (from Rosenberg, 1982).

steps logically provide ways of adjusting better to the climate, even as it is today.

One cannot rule out the possibility that some lands now too arid for cultivation of food crops may indeed become more usable for these purposes in the future. However, there is no more evidence to support that assumption than there is to support the idea, popularized by the media, that productive lands in the U.S. Midwest and Great Plains are *certain* to become drier and less productive.

Although it may be too early to be changing American agriculture, it is certainly not too early to begin systematic, orderly, and rigorous study of the vulnerability of our agriculture, the possible impacts on agriculture of climatic changes described in credible scenarios, and the technological options that may be required if we are to cope with such changes. On the basis of such studies and as the evidence becomes stronger and the specificity of regional projections greater, a sound set of policy options can be developed.

Further, we must not assume that climate change will occur as a series of discontinuous steps. We will not awake one New Year's Day to a new climate. Changes may be gradual and monotonic, but there may be some rapid changes and surprises in store as well. Whatever the rate and nature of the changes, by the time we know what is happening, world and U.S. agriculture will be different than they are today. Therefore it is very important that our research and policy thinking not be based on the imposition of a future climate on today's agriculture. Rather, it is necessary that serious attempts be made to forecast the kinds of agriculture, the needs for commodity production, and the technological tools that will be available to us when climate has actually changed. One aim of RFF's new Climate Resources Program is to develop the analytical techniques needed for systematic analyses of the problems described above.

One other point deserving particular attention is this: American agriculture and that of the developed countries may indeed be severely strained or otherwise affected as a result of climatic change in the coming decades. But the resources that most developed countries have available to help them cope with change are very great when compared with those available to the less developed countries. Indeed, too many of the latter countries already live too close to the margins of famine to be able to absorb the shocks that climate change could impose on their food producing capacity. For that reason it is most consequential that, in our efforts to assist development in such nations, the possibility of climate change, both stressful and benign, be factored into analysis and planning.

One final thought and not a very original one: an investment of research effort to learn more about the vulnerability to climatic stress of U.S. and global agricultural systems and about ways to mitigate the effects of such stress is sorely needed. This is true whether or not the climate changes, since food production throughout the world is and is likely to remain extremely sensitive to climatic fluctuations.

POLICY IMPLICATIONS

There is nothing in the predictions of the climate change community to suggest that we should reduce emphasis on soil and water conservation programs. One near certainty—global warming—means that aridity will increase in some regions. In those regions, vulnerability to wind erosion will also increase. The conservation reserve program and sodbuster provisions are likely to be needed as much in the future as they are today.

Conservation of groundwater should be emphasized, especially in aquifers, like the Ogallala, that are only slowly rechargeable. Vast quantities of water in storage may provide a buffer to lessen the negative impacts of greater aridity in the mid-latitudes of North America, should climate change occur as some global climate models suggest.

New varieties of currently cultivated food and feed crops and new species may be needed to facilitate adaptation to climatic change. Maintenance of current gene pools and protection of natural biodiversity provide insurance that the needed genetic materials will be available. Plant breeding programs should increase their emphasis on improving tolerance to heat and moisture stress. Biotechnology, with appropriate controls in place, can contribute to this goal.

Agencies charged with management of our natural resources should identify which of their programs could be affected by changes in climate. Research efforts should be initiated to assess the potential impacts of climatic change on these resources and programs as the basis for contingency planning. Further, agriculture is one of the sources of greenhouse gases—methane emissions from rice paddies and ruminant animals and enhanced nitrous oxide emissions from fertilized soils. Research is needed to quantify the rates of emissions from various agricultural systems and to find ways to reduce them.

Climate change will be a lottery. The state of the science is yet too primitive to allow for reliable prediction of which nations and regions within nations will be net beneficiaries and which net losers. The implications for agriculture are twofold. First, comparative advantage in the production of particular crops may shift from one nation or region to another. The best insurance is readiness to introduce new crops to replace those that can no longer be produced profitably. Second, if climate change continues unabated we will all be numbered, sooner or later, among the losers.

ACKNOWLEDGMENTS

Some of the research reported here was conducted with support of the National Science Foundation/Division of Atmospheric Sciences and the National Climate Program Office. I thank Dr. Pierre Crosson of Resources for the Future for his review of this paper and suggestions for improvement.

REFERENCES

Evans, L. T. 1985. "The Variability of Cereal Yields as Influenced by Plant Breeding, Agronomic Improvement, and Socio-Economic Factors: Concluding Assessment." Paper presented at the Workshop on Sources of Increased Variability in Cereal Yields, IFPRI/DSE, Feldafing, Germany, November 26–29 (reprint, mimeo).

Kessler, E., D. Y. Alexander, and J. F. Rorick. 1978. "Duststorms from the U.S. High Plains in Late Winter 1977—Search for Cause and Implications," *Proceedings of the Oklahoma Academy of Science* 58, pp. 116–128.

National Academy of Sciences. 1976. *Climate and Food: Climatic Fluctuation and U.S. Agricultural Production* (Washington, D.C., Board on Agriculture and Renewable Resources, National Research Council).

Rosenberg, N. J. 1982. "The Increasing CO_2 Concentration in the Atmosphere and Its Implication on Agricultural Productivity. II. Effects Through CO_2-Induced Climatic Change," *Climatic Change* 4, pp. 239–254.

———. 1986. "Climate, Technology, Climate Change, and Policy: The Long Run," in C. F. Runge, ed., *The Future of the North American Granary* (Ames, Iowa State University Press).

Schlesinger, M. E., and J. F. B. Mitchell. 1985. "Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide," in M. C. MacCracken and F. M. Luther, eds., *Projecting the Climatic Effects of Increasing Carbon Dioxide*. DOE/ER-0237 (Washington, D.C., U.S. Department of Energy, Carbon Dioxide Research Division).

Journal of
Environmental Quality

VOLUME 17 • OCTOBER-DECEMBER 1988 • NUMBER 4

REVIEWS AND ANALYSES

Implications of a Global Climatic Warming for Agriculture: A Review and Appraisal

B. Smit,* L. Ludlow, and M. Brklacich

ABSTRACT

Recently it has been recognized that changes in the chemical composition of the atmosphere are likely to alter the earth's climate, and that these alterations may have severe implications for agriculture and other economic activities. This has stimulated research into the possible consequences of altered climatic regimes on several attributes or components of agri-food systems. Current consensus suggests that a global climatic warming, induced by increased concentrations of CO_2 and other "greenhouse" gases, is likely, and hence the possible implications of warmer climates for agriculture has received considerable attention. Several analytical procedures have been employed in these studies and it is timely to assess the characteristics and achievements of these independent efforts. This paper classifies and reviews studies that examine the implications of climatic warming for agriculture. Three approaches to assessment are recognized. Crop yield analysis identifies the effects of a specified change in climate on productivity levels for individual crops in particular locations. Spatial analysis examines the implications of climatic warming for the area and location of lands suitable for crop production. Agricultural systems analysis focuses on the relationships among components of agri-food systems. Much remains to be learned about the effects of climatic warming on agriculture. The use of existing information to develop a comprehensive analysis is hampered by differences in analytical approaches and in climatic change scenarios, and by the virtual absence of information on the possible implications of climatic change on agriculture in developing nations. Nevertheless, current evidence suggests that a warmer climate could create a more favorable environment for wheat (*Triticum aestivum* L.) and grain corn (*Zea mays* L.) in Canada, Northern Europe, and the USSR, and restrict opportunities in the USA.

The possible implications for agriculture and food production of changes in atmospheric chemistry have prompted concern worldwide. This concern has stimulated considerable research into the direct impacts of ozone (O_3), carbon dioxide (CO_2), sulphur dioxide (SO_2), and acid deposition on various aspects of agri-food systems. Some studies have examined the effects of these chemical changes on crop growth and yields (Heagle et al., 1983; Irving, 1983; Rogers et al., 1983), whereas others have assessed the subsequent implications for agricultural production (Forster, 1984; Heck et al., 1983; Ludlow and Smit, 1987). These studies suggest that adjustments to the chemical composition of the atmosphere may have serious consequences for agriculture in many regions of the world.

In addition to these direct impacts, there is a growing interest in the extent to which chemical changes might affect other atmospheric properties and how these adjustments, in turn, will alter agriculture. For example, the impacts on global climatic patterns of increases in infrared absorbing or *"greenhouse" gases* have been the focal point for many studies investigating the indirect effects of atmospheric alterations (Hare, 1983; Harrison, 1984; Liverman, 1986; Pittock and Nix, 1986; Rosenzweig, 1985; Williams et al., 1988). Although there is con-

---

B. Smit, Dep. of Geography, Univ. of Guelph, Guelph, ON N1G 2W1 Canada; and L. Ludlow and M. Brklacich, Land Evaluation Group (LEG), Univ. School of Rural Planning and Development, Univ. of Guelph. Contribution from LEG, Univ. of Guelph. Research was conducted at the Univ. of Guelph and supported by the Atmospheric Environment Service of Environment Canada, the Social Sciences and Humanities Research Council, the Ontario Ministry of Agriculture and Food, and the Land Resource Research Centre of Agriculture Canada. Received 9 Nov. 1987. *Corresponding author.

Published in J. Environ. Qual. 17:519-527 (1988).

siderable uncertainty regarding the magnitude and regional effects of these changes (Schlesinger and Mitchell, 1985), existing evidence suggests that increases in greenhouse gases will contribute to warmer and drier climates in midlatitude regions such as the midwestern USA, southern Europe, and Asia, whereas the higher latitudes will in all likelihood be characterized by a warmer but somewhat wetter climate (NRC, 1982). Such changes in climate could have major implications for agriculture worldwide, and research is now being directed toward investigating these potential effects (Parry and Carter, 1988).

Studies have assessed the possible consequences of altered climatic regimes on various attributes or components of agri-food systems, ranging from those that assess the impacts of modified climates on crop yields to those that estimate the effects on global agricultural production and trade. A sufficient body of information now exists to warrant a review, which would contribute to the development of climatic impact assessment by providing a common ground for comparative studies, by summarizing current knowledge on this growing environmental concern, and by facilitating the development of an effective research agenda.

This article classifies and reviews studies that examine the implications of a greenhouse gas-induced global climatic warming on agriculture. Enrichment effects resulting from changes in atmospheric chemistry such as increases in plant photosynthesis and water-use efficiency (Kimball, 1983; Lemon, 1983; Rogers et al., 1983; Rosenberg, 1981) are not considered here; nor are second-order impacts, such as those that could occur from sea level rises (Postel, 1986) or increases in agricultural pests (Decker et al., 1986). Such cumulative impacts are beyond the scope of this article.

Of necessity, this review does not include all studies undertaken in this field, but at least provides examples of the major forms of analysis employed. This article presents an appraisal of the approaches with respect to the types of information they provide and their applications, summarizes results of impact assessments, and indicates the possible implications of warmer climates on the opportunities for crop production for major agricultural regions of the world.

CLASSIFICATION OF IMPACT STUDIES

Studies providing information on impacts of climatic change on agriculture vary in many respects. They differ according to their approach to assessment, the climatic change scenarios they specify, their geographic coverage, and the attributes of the agri-food sector they consider. This classification helps clarify the types of information available, and summarizes the possible effects of climatic warming in major regions of agricultural production.

Approach to Assessment

Although the provision of a better understanding of the relationship between climate and agriculture is a common link among virtually all studies investigating the impacts of climatic change on agriculture, no one approach to assessment has gained universal acceptance. In this review, the following three approaches are recognized:

1. Crop yield analysis
2. Spatial analysis
3. Agricultural systems analysis

Crop yield analysis represents the most common approach, and a variety of analytical techniques have been employed to examine the possible effects of climatic change on crop productivity levels (Bootsma et al., 1984; Lough et al., 1983). Spatial analysis investigates the consequences of altered climates on the location of the agricultural frontiers (Blasing and Solomon, 1984; Newman, 1980), whereas agricultural systems analysis focuses on the linkages among various components of the agri-food sector (Liverman, 1986; National Defense Univ. [NDU], 1983).

Climatic Change Scenarios

The climatic change scenarios employed in impact studies can be characterized by the methods utilized to estimate climatic modifications and by the nature of the climatic change. The magnitude and extent of any future climatic change is not known with certainty. A variety of climatic variables such as land and sea surface temperatures, air temperatures, precipitation, atmospheric pressure, and cloudiness (Lamb, 1986) could be affected. Hence, it is not uncommon for impact studies to identify several scenarios of climatic change. Many methods for identifying these scenarios have been employed (Lamb, 1986). Some studies rely on general circulation models (GCMs) to identify levels of future climatic change (Blasing and Solomon, 1984; Rosenzweig, 1985; Williams et al., 1988), whereas others use past climatic periods as analogues for future conditions (Lough et al., 1983; Palutikof et al., 1984). Climatic changes have also been identified by specifying parametric or incremental changes in climatic variables, such as temperature and precipitation (Bootsma et al., 1984; Parry, 1978), and by utilizing expert opinion (NDU, 1978).

The range of climatic properties considered tends to vary according to the purpose of the assessment and the analytical techniques used to specify the climatic change scenario. Earlier studies (Parry, 1978; Ramirez et al., 1975) tended to consider a few macroclimatic variables, usually temperature and precipitation. More recently (Land Evaluation Group, 1986; Williams et al., 1988), the range of agroclimatic properties considered in the impact assessments has been expanded to include many of the other relevant factors that greatly influence crop growth and development, such as length of growing season and soil moisture.

Geographic and Sector Coverage

The geographic coverage and the number of agricultural activities considered are ultimately influenced by the intended application of the investigation.

Geographic coverage can range from individual plants and farm operations (Bootsma et al., 1984; Terjung et al., 1984a, b) to major food producing regions (Blasing and Solomon, 1984; Rosenzweig, 1985). The range of agricultural activities can vary from particular crops (Parry, 1978; Waggoner, 1983) to a comprehensive assessment of many of the major primary production activities (Williams et al., 1988).

REVIEW AND APPRAISAL

The various approaches and perspectives implicit in studies that examine the relationships between climatic warming and agriculture have provided a better understanding of the potential implications of warmer climates for selected components of food production systems. However, the variability in approach, design, and scope, which characterizes these partial analyses, has contributed to some confusion; the melding of these studies into a comprehensive assessment is both a needed and contentious task.

Table 1 characterizes studies that assess the effects of global climatic warming on agriculture. To facilitate the review and appraisal process, studies summarized in Table 1 are discussed initially according to their approach to assessment: crop yield analysis, spatial analysis, and agricultural systems analysis. This review also considers the climatic change scenario employed, the climatic properties considered, and the geographic and sector coverage of each study.

Crop Yield Analysis

Crop yield analysis estimates the effects of altered environments on crop productivity levels and has been employed widely in climatic impact assessments. It is appropriate to subdivide crop yield analysis into studies based on surveys of expert opinion and studies relying on crop productivity models.

Many assessments on the impacts of climatic warming on crop yields are made by experts, based on their accumulated knowledge of the expected climatic change and the climatic requirements of crops. The NDU (1980) study exemplifies crop productivity analysis employing expert opinion. This approach was utilized to estimate both the extent of expected climatic warming and the concomitant impacts on selected crop yields. Although this study has been widely distributed among policy makers in many countries, its validity and the reliability of its findings have been questioned (Stewart and Glantz, 1985). The major concerns stem from the use of averaging procedures to develop the climatic change scenarios and the yield responses. It is suspected that the approach has projected a future that will be inconsistent with the magnitude of change that is likely. More specifically, it is believed by many that the NDU study underestimates possible differences from the present climate. However, by employing rigorous techniques to illicit and utilize the opinions of experts, particularly in the aggregation of differing projections, expert opinions could be an effective and inexpensive means for estimating effects of climatic change on crop yields.

The application of crop productivity models to climatic impact assessment includes procedures based on statistical (regression) and/or simulation techniques, and to a large extent, follow the development of crop productivity models in general (Baier, 1979; Biswas, 1980). Regression models estimate yields as a function of multiple predictor variables. By using historical climatic and yield data for specific crops in particular areas, regression equations have been developed and used to predict the changes in yields expected due to alterations in climate (Lough et al., 1983; Santer, 1984). Among the reservations regarding the application of regression-based crop models are the lack of true independence among the predictor variables, especially those related to agroclimatic properties, such as length of growing season and soil moisture, and the extension of the statistical relationships beyond the range of conditions for which they were developed (Parry and Carter, 1988).

Simulation models have also been applied to assess the impacts of climatic change on crop yields (Terjung et al., 1984a, b; Waggoner, 1983). These models are developed by combining a set of mathematical equations based on experiments or knowledge of specific plant processes (photosynthesis, respiration, and transpiration) and their interactions with the environment (climate and soils). Simulation models are based on crop-climatic processes and hence can be applied to environmental conditions other than the current. Although the capacity of simulation models to capture and integrate specific plant processes is still quite limited, this approach to productivity modelling is ultimately better suited to estimating yield changes due to climatic modifications than empirical-statistical regression models (Parry and Carter, 1988).

Many studies have been performed to assess the impacts of climatic warming on crop yields (Table 1). Results from these studies indicate that relative to current technologies or management practices, the yields of major crops in North America and Europe may diminish as a consequence of climatic warming. For example, grain corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) yields in the midwestern USA and Canada will tend to decrease as climate becomes warmer and drier (Benci et al., 1975; Bootsma et al., 1984; Ramirez et al., 1975; Williams et al., 1988). Current yields of these crops are also expected to decrease in most regions of Western Europe (Lough et al., 1983; Santer, 1985). Of course, changes in production inputs and producer response to climatic change (e.g., technological advances that might reduce the vulnerability of particular crops to heat and moisture stress and adoption of crops more suitable to an altered climate), could tend to counterbalance these potential declines in yields.

The gradual change in climatic norms due to elevated levels of greenhouse gases could allow time for changes in agricultural patterns and other management practices to occur. Studies that simultaneously consider climatic change and adjustments to technology and management suggest that a global climatic warming could contribute

Table 1. Studies on the impacts of climatic change on agriculture.

	Approach			Altered climate?						
Study	Crop yield	Spatial shift	Agric. systems	Source‡	ΔT§	ΔP¶	Other#	Geographic coverage	Crop production categories	Summary of findings
Benci et al., 1975	X			Inc.	+1°C +2°C	+10% +20%	No	Midwestern USA	Grain corn yields	Yields of grain corn decrease approximately 10 to 20%.
Blasing & Solomon, 1984		X		GCM	+3°C	+8 cm	Yes	Midwestern USA	Grain corn belt	The USA Corn Belt will shift to the northeast, possibly into Ontario.
Bootsma et al., 1984	X			Inc.	Yes	Yes	No	Canada	Yields of: Grain corn Forage Potato Cereal Oilseed	Yields of crops decrease in most regions of Canada.
IIASA/UNEP Project										
–Bergthorsson et al., 1988	X		X	GCM	+4°C	+15%	Yes	Iceland	Yields of: Hay Pasture Livestock carrying capacity and feed requirements	Hay yields increase 66% and pasture yields increase 49 to 52%, resulting in substantial increases in carrying capacity of pastures and rangelands, and substantial decreases in feed requirements for horses, sheep, and cattle
–Kettunen et al., 1988	X		X	GCM	+33%	+50%	Yes	Finland	Yields of: Spring wheat Barley Oat National farm income	Spring wheat yields increase 20%, barley yields increase 14%, and oat yields increase 13%, resulting in a 12 to 27% increase in national farm income if prices do not change.
–Pitovranov et al., 1988	X		X	GCM	+2.2°C +3.7°C	+36% +50%	Yes	USSR	Yields of: Winter rye Spring wheat	Winter rye yields increase by about 6% with no change in management, and increase 50 and 57% with adjusted management (e.g., increased fertilizer applications); spring wheat yields decrease 3% with no change in management and increase 16 and 26% with adjusted management (e.g., introducing new crop varieties).
				Inc.	+1°C	No	No		Yields and production of: Winter wheat Barley Oat Corn Hay Potato Other vegetables	Winter wheat yields increase about 30%, corn yields increase about 10%, and the other crops show only small changes in yields. Production of winter wheat and grain corn increase, while at the same time production of barley, oat and potato decreases. Hay and vegetable production remain about the same.
–Williams et al., 1988	X		X	GCM	+3.5°C +3.6°C	+0% +19%	Yes	Saskatchewan, Canada	Spring wheat: Yields Production Farm income Employment	Yields of spring wheat decrease 4 to 29% depending on soil type and these decreases result in a provincial spring wheat production decrease of 15%, a provincial farm household income decrease of 7%, and decreases in employment in the agricultural sector of 0.8% and in all other sectors of 0.5%.
–Yoshino et al., 1988	X	X	X	GCM	+3.5°C	No	Yes	Japan	Rice: Yields Net biomass prod. National supply National stock	Rice yields increase 2 to 5%, and the cultivation limit rises about 500 m, resulting in a 9% increase in relative total net production, a 3% increase in national rice supply, and a 191% increase in national rice stock.
Land Evaluation Group, 1985, 1986	X		X	GCM	Yes	Yes	Yes	Ontario, Canada	Yields and production of: Grain corn Barley Oat Winter wheat Soybean Hay Fodder corn Potato	Crop yields decrease in most regions of Ontario, except northern and eastern Ontario, where yields of most crops could increase. Opportunities for the production of grain corn, wheat, and soybean would be enhanced in Northern Ontario, and opportunities for the production of most crops would diminish in the rest of Ontario. Overall, given current production patterns, all crops would show decreases in provincial productions and value of production.
Liverman, 1986	X		X	Hypothetical: Yield changes are used as surrogates for climatic changes				World	Grain production and trade	Regional (e.g., USA) and global decreases in crop yields, reflecting abrupt changes in climate, could have adverse effects on the world food system. For instance,

(continued on next page)

Table 1. Continued.

Study	Approach			Altered climate†				Geographic coverage	Crop production categories	Summary of findings
	Crop yield	Spatial shift	Agric. systems	Source‡	ΔT§	ΔP¶	Other#			
										world starvation could increase. On the other hand, gradual changes in yields reflecting slow, smooth climatic changes seem to have little impact on the world food system. Such changes are absorbed by the system.
Lough et al., 1983	X			HA	Yes	Yes	Yes	Wales, England	Yields of: Wheat Barley Oat Hay Turnip, swede	Most crops show decreases in yields.
National Defense Univ., 1978, 1980, 1983	X		X	EO	Yes	Yes	No	World	Grain yields, production, trade, and prices	Grain yields decrease in most regions of the world. Major exceptions are Canada and the USSR, where wheat yields increase. A consequence of these regional changes in yields is changes in production. Grain production decreases in regions such as Africa, Australia, Central America, India, the USA, and Western Europe; and increases in Argentina, Canada, China, Eastern Europe, and the USSR. Changes in production have implications for trade and prices of grain as well. Canada, Argentina, and Brazil increase grain exports. Europe, Africa, and Asia increase grain imports, and the USSR and China shift from importing to exporting nations. Prices of wheat and the coarse grains decrease by about 5% and rice prices increase by about 2 or 3%.
Newman, 1980		X		Inc.	+1°C	No	No	Midwestern USA	Grain Corn Belt	For every 1°C warming, the USA Corn Belt would shift 144 km to the north and 100 km to the east. This amounts to about a 175 km shift toward the northeast.
Parry, 1978		X		Inc.	+1°C	No	No	Upland Britain	Critical limits	In total, about 2 million ha (about one-third) of Britain's improved moorland, which are at present submarginal for cereals in terms of summer warmth, would become marginally viable for cereal production.
Ramirez et al., 1975	X			Inc.	+1°C +2°C	+10% +20% +30%	No	Midwestern USA	Wheat yields	Wheat yields decrease 13 to 20% in the drier states of Illinois and Indiana, and increase up to 10% in the wetter areas of Kansas and North Dakota.
Rosenzweig, 1985		X		GCM	Yes	Yes	Yes	Canada USA Mexico	North American Wheat Belt	There is greater expansion of the winter wheat belt into Canada. The major wheat regions in the USA will remain about the same. However, Mexico is classified as a vulnerable region, because high temperature stress could decrease wheat production in the country.
Santer, 1985	X			GCM	Yes	Yes	Yes	Western Europe	Winter wheat yields	Winter wheat yields decrease in most of the major wheat-producing countries in Western Europe (e.g., France, Germany, and Italy).
Terjung et al., 1984a, b	X			Inc.	+1°C	No	No	World	Yields of: Grain corn Rice Wheat	Seasonal yields of all crops decrease up to about 8%.
Waggoner, 1983	X			Inc.	+1°C	−10%	No	Midwestern USA	Yields of: Spring wheat Winter wheat Soybean	Yields of all crops decrease up to about 10%.

† Only scenarios that are consistent with a CO_2-induced global climatic warming are included.
‡ Abbreviations: Inc. = incremental; GCM = general circulation model; HA = historical analogue; EO = expert opinion.
§ ΔT = temperature change.
¶ ΔP = precipitation change.
# Other agroclimatic changes were also considered.

to increases in yields of major crops grown in many high-latitude regions (Table 1). In the USSR, for example, winter rye (*Secale cereale* L.) and spring wheat yields could increase substantially by increasing fertilizer applications and introducing new crop varieties (Pitovranov et al., 1988). In Canada it has been suggested that by switching from spring to winter wheat the problems associated with increased moisture stress under an altered climatic regime could be alleviated and yields could be enhanced (Parry et al., 1985).

So far, the crop yield approach to assessing the impacts of climatic warming on agriculture has focused on major crops currently produced in North America and Europe. Little information is available regarding the vulnerability to climatic change of many crops, including such important ones as soybean [*Glycine max* (L.) Merr.] and rice (*Oryza sativa* L.). Despite the incompleteness of current evidence, crop yield studies provide useful information. Results indicate that increased moisture stress due to warmer and drier conditions could reduce the yields of current varieties of major crops in many regions of the world. If research is directed toward the development of drought-resistant crop varieties and water-conserving farm management practices, these yield reductions could possibly be abated in midlatitude regions. At higher latitudes, such as regions in Canada and the USSR, yields could increase by introducing field practices and crop varieties already existing at midlatitudes.

Spatial Analysis

Spatial analysis examines the implications of climatic warming on the area and location of lands suitable for agricultural production. One method for assessing these implications is the use of spatial analogues. This technique involves identifying analogue regions that currently experience conditions similar to those predicted in another region given a future climatic warming.

Spatial analogues can provide information on likely impacts of climatic warming on agriculture, such as the possibilities for introducing new crops into an area. For example, a study by the Land Evaluation Group (1986) found that under an environment of increased concentrations of greenhouse gases the temperature and precipitation levels in southern Ontario, Canada, would resemble those currently experienced in parts of the eastern USA, and many of the agroclimatic barriers that effectively limit the production of vegetable and horticultural crops in Ontario would be removed. This sort of spatial analysis provides an effective means for indicating the extent to which a climatic change might influence the biophysical opportunities for production, but it would of course be inappropriate to conclude that climatic change will cause an adjustment to cropping patterns. Cropping patterns are sensitive not only to climatic conditions, but also to soil characteristics and socioeconomic conditions such as demands for crop products.

Another method for evaluating changes in the area and location of agricultural production is to examine the movements of agricultural margins under alternative climatic warming scenarios. The first step in such an analysis involves identifying a condition or set of conditions that effectively constrain production at agricultural margins. These conditions may be biophysical, such as frost-free period, or socioeconomic, such as the extent to which climate implies a risk to production. Then, threshold or critical values for specific agricultural activities are established for each of the selected conditions. For biophysical conditions, the thresholds are usually derived from a particular crop requirement for maturation, whereas the socioeconomic thresholds identify acceptable levels of risk associated with temporal variability in climate. The area and location of lands suitable for an agricultural activity for a specified climate can be estimated by mapping these thresholds as isopleths. The sensitivity of suitable lands for agriculture to climatic warming can then be examined by repeating the analysis for two or more climatic scenarios.

Newman's (1980) examination of the implications of climatic warming on the location of the USA Corn Belt typifies spatial analysis employing thresholds for biophysical conditions. The prevailing thermal and moisture regimes effectively define the current margins of the USA Corn Belt, and Newman employed these boundaries to identify critical values for growing degree days (GDD) and potential evapotranspiration (PE). By increasing growing season temperatures by 1 °C the critical GDD isopleth shifted northward and the critical PE isopleth eastward. These correspond to an estimated migration in the Corn Belt of about 175 km toward the northeast.

Blasing and Solomon (1984) also used spatial analysis to investigate the effects of climatic warming on the biophysical conditions that define the USA Corn Belt. This study employed the same threshold criteria as the Newman study, but specified a different climatic change scenario. A 3 °C increase in temperature and a corresponding increase in precipitation of 8 cm were identified as the climatic change scenario by using a GCM and assuming a twofold increase in atmospheric CO_2. The analysis by Blasing and Solomon (1984) also reveals that the USA Corn Belt could shift towards the northeast, although the magnitude of displacement is not as great as predicted by Newman.

The studies by Newman (1980) and Blasing and Solomon (1984) indicate that the USA Corn Belt could shift northeast, possibly into Canada (Table 1). The USA Wheat Belt is expected to show similar shifts if climate is to warm (Rosenzweig, 1985) (Table 1). These shifts in cropping patterns imply that the higher yielding USA corn varieties could replace Canadian corn varieties, and that Canada could switch from producing primarily the lower-yielding spring wheats to producing winter wheats. Consequently, opportunities for producing corn and wheat could increase in Canada, while prospects for producing these crops in the USA may become less favorable.

The location of agricultural production zones may also be interpreted from socioeconomic perspectives. As an example, Parry (1978) used failure frequency as the socioeconomic condition by which to measure the critical limits for oat (*Avena sativa* L.) cropping in Britain (Table 1). Any probability of crop failure >0.3 was considered to be "too risky" for continuing or viable oat production. The analysis revealed that a 1 °C increase in temperature would elevate this risk level isopleth 140 m. This would increase the land area in Britain that could physically and economically support oat production by about 2 million ha.

As yet, spatial analysis of agricultural zones has been applied only at the regional scale. However, spatial analysis could feasibly be conducted to study the impacts of climatic warming globally. Emanuel et al. (1985) has used this analysis to study the impacts of climatic warming on the worldwide distribution of natural vegetation zones. It has been suggested that similar types of spatial analysis may provide a basis for agricultural evaluation of climatic warming (Oram, 1985; Williams, 1985). Expanding these studies to all regions would provide insight into the opportunities for introducing new crops into many areas.

Agricultural Systems Analysis

Agricultural systems analysis focuses on assessing the impacts of climatic changes on multiple agricultural activities and on the functioning of the agri-food sector. Studies using agricultural systems analysis attempt to go beyond assessments based on crop yield and spatial analyses by providing information on many aspects of the agricultural sector, including total production, prices, trade patterns, and employment.

Historical analogues, which utilize responses to previous climatic changes as a means to suggest potential adjustments to future climates, represent one technique applied to agricultural systems analysis. For example, Butzer (1980) and Rosenberg (1982) have attempted to gain insight into the possible implications of a climatic warming on agriculture in North America's Great Plains by examining agricultural adaptations during the Dust Bowl of the 1920s and early 1930s. Although these sorts of analyses can provide a better understanding of responses to a specific set of conditions, their applicability to a future climatic warming is limited. The climatic changes experienced during the Dust Bowl are characterized by relatively abrupt adjustments, whereas climatic modifications stemming from increasing levels of greenhouse gases are occurring at a relatively slow rate. Socioeconomic conditions affecting agriculture during this era are considerably different from the current, let alone future technologies, management practices, and marketing conditions. The agricultural response to short-term deviations from climatic norms may be quite different from the response to gradual changes in the norms. The opportunities for direct application of historical analogues to estimating the evolution of agricultural systems under a warmer climate are limited.

Mathematical models represent another group of techniques that have been employed to trace the effects of climatic change on biophysical, economic, and/or social components of agricultural systems. At the farm level, studies by Williams et al. (1988) in Saskatchewan and the Land Evaluation Group (1986) in Ontario, Canada, used programming models to investigate the effects of climatic warming on farm income and profitability. Both studies employed output from GCMs in the development of scenarios for climatic change. The Saskatchewan study assessed the implications of climatic change on 29 farms representing major farming activities throughout the province. The Ontario study investigated only one type of farming, but the range of climatic change scenarios was expanded to consider adjustments to climatic variability as well as norms. Overall, both studies suggest that relative to current technologies and management practices, a climatic warming could increase the economic risks for production in the Canadian grain sector. Such analyses illustrate the need and opportunities to address issues related to the distribution of impacts stemming from climatic change (Waterstone, 1985).

The recently completed study funded by the International Institute of Applied Systems Analysis (IIASA) and the United Nations Environmental Programme (UNEP) is a major example of a study utilizing agricultural systems analysis at regional and national levels (Table 1). Various techniques were employed to assess the implications of future climatic warming for agriculture in the high-latitude regions of Canada (Saskatchewan), Iceland, Finland, the USSR, and Japan (Parry and Carter, 1988). In all studies, crop yield analysis was first employed to estimate the impacts of climatic warming on selected crops. These estimates were then applied to assess the downstream effects on regional and national economies. Mathematical models were used to determine impacts on aggregate production and income for Saskatchewan, the USSR, and Japan, whereas the studies conducted for Finland and Iceland relied on expert opinion.

Generally, the results of the IIASA/UNEP project suggest that effects of climatic warming on agriculture in high-latitude regions are beneficial. In Iceland the livestock-carrying capacity of pastures and rangelands are estimated to increase substantially (Bergthorsson et al., 1988). Total farm income for Finland and Japan are estimated to increase due to enhanced production of barley (*Hordeum vulgare* L.) and rice, respectively (Kettunen et al., 1988; Yoshino et al., 1988). In the USSR, wheat production could be enhanced greatly under a warmer climatic regime, and corn production could also increase but to a lesser extent. At the same time, oat and barley production could decrease slightly (Pitovranov et al., 1988). The Saskatchewan study reveals that prospects for spring wheat production could decrease, but the opportunities for introducing new crops or crop varieties afforded by warmer climate would increase the province's overall potential for agricultural production (Williams et al., 1988).

Global equilibrium models (GEMs) have been employed by the NDU (1983) and Liverman (1986) to assess agricultural systems for an international perspective. These models do not consider climate explicitly, but climatic warming can be considered by conducting crop yield analyses and using these findings as inputs to the GEM.

The NDU applied the grain, oilseed, and livestock (GOL) GEM to identify the effects of a climatic warming on regional production, trade, and prices of grain. The findings of the NDU (1983) study tend to concur with those studies that investigate the implications of climatic change for individual nations. That is, the altered climate would likely modify the structure of agricultural systems. The most notable adjustments could include a more favorable trading position for the Canadian and USSR grain sectors, reductions in grain exports from the USA, declines in the world price for wheat and coarse grains, and slight increases in the market price for rice.

The primary purpose of Liverman's (1986) research was to investigate the applicability of GEMs for climatic impact assessment. The International Futures Simulation (IFS) model was employed, and the study includes an appraisal of the effects on the international structure of agricultural systems, given a gradual climatic warming that is consistent with increasing levels of atmospheric CO_2. The major finding is that global food stocks would decline and contribute to increases in food deficits, especially in southern Asia.

Agricultural systems analysis provides an opportunity to extend the utility of crop yield and spatial analyses, and to assess the subsequent implications for farm incomes, aggregate production, and international trading prospects. However, current knowledge regarding the possible impacts of climatic warming on agricultural systems is extremely fragmented, limited to a small set of future scenarios for climate and other conditions, and focused almost exclusively on high-latitude regions. There is considerable prospect for improving comprehension of agricultural sensitivities to climatic warming via the development of systems analysis to include other regions and a wide range of scenarios.

CONCLUSIONS

Despite the many research efforts, firm conclusions regarding the implications of future global climatic warming for agriculture are difficult to draw. Climatic impact assessments have not been conducted for many regions, particularly developing nations in Asia and Africa, and hence the response of crops and agricultural systems to climatic change in these areas is not known. Even in areas of North America and Europe, where considerably more research has been conducted, there is little certainty in knowledge about the implications of climatic warming for agriculture. Differences in the approaches in the agricultural activities covered and in geographic coverage make it difficult to compare results and develop a comprehensive appraisal of the potential consequences of climatic warming. Current knowledge indicates that the impacts of this warming on agriculture will vary from crop to crop, location to location, and system to system.

Evidence, although incomplete, suggests that conditions for producing crops such as grain corn and wheat may become more favorable in Canada, Northern Europe, and in the USSR, while at the same time opportunities for producing these crops in the midlatitude regions of the USA and Western Europe may diminish.

It is now widely accepted by environmental scientists that global climatic change is prompted in part by increasing levels of atmospheric CO_2 and other "greenhouse" gases. This review and appraisal has focused on the agricultural implications of the consequent climatic warming, and has not investigated the other direct and indirect impacts of changes in the atmosphere that ultimately affect crop growth and agricultural production. Evidence elsewhere suggests that dry matter production and crop yields could increase in CO_2-enriched environments (Kimball, 1983; Kramer, 1981; Lemon, 1983; Prior et al., 1987), and Sionit et al. (1987) and Kimball et al. (1987) illustrate the need to consider the combined influences of changes to climatic and atmospheric quality. There is an opportunity to extend this review and appraisal to consider the multiple and cumulative effects stemming from atmospheric change. Clearly, a better understanding of the effects of human activities on climate and of the impacts of altered climates on activities such as agriculture will better enable societies to prepare for and adapt to future climates.

ACKNOWLEDGMENT

This article benefited from reviewers' suggestions and input from D. Bond.

REFERENCES

Baier, W. 1979. Note on the terminology of crop-weather models. Agric. Meteorol. 20:137–145.

Benci, J.F., E.C.A. Runge, R.F. Dale, W.G. Duncan, R.B. Curry, and L.A. Schaal. 1975. Effects of hypothetical climatic change on production and yield of corn. p. 4-3–4.36. *In* Climatic Impacts Assessment Project (CIAP), Impacts of climatic change on the biosphere. U.S. Dep. of Transportation, Washington, DC.

Bergthorsson, P., H. Bjornsson, O. Dyrmundsson, B. Gudmundsson, A. Helgadottir, and J.V. Jonmundsson. 1988. The effects of climatic variations on agriculture in Iceland. p. 381–509. *In* M.L. Parry et al. (ed.) The impact of climatic variations on agriculture. Vol. 1. Assessment in cool temperate and cold regions. Reidel Publ. Co., Dordrecht.

Biswas, A.K. 1980. Crop-climate models: A review of the state of the art. p. 75–92. *In* J. Ausubel and A.K. Biswas (ed.) Climatic constraints and human activities. IIASA Proc. Ser. 10, Pergamon Press, New York.

Blasing, T.J., and A.M. Solomon. 1984. Response of the North American Corn Belt to climate warming. Prog. Biometeorol. 3:311–321.

Bootsma, A., W.J. Blackburn, R.B. Stewart, R.W. Muma, and J. Dumanski. 1984. Possible effects of climate change on estimated crop yields in Canada. Research Branch, Agriculture Canada, Ottawa.

Butzer, K.W. 1980. Adaptation to global environmental change. Professional Geographer 32:269–278.

Decker, W.L., V.K. Jones, and R. Achutuni. 1986. The impact of climatic change from increased atmospheric carbon dioxide on American agriculture. DOE/NBB-0077. Dep. of Atmos. Sci., Univ. of Missouri, Columbia, MO.

Emanuel, W.R., H.H. Shugart, and M.P. Stevenson. 1985. Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. Clim. Change 7:29–43.

Forster, B.A. 1984. An economic assessment of the significance of long-range transported air pollutants for agriculture in Eastern Canada. Can. J. Agric. Econ. 32:498–525.

Hare, F.K. 1983. Future climate and the Canadian economy, climatic change in Canada 3. Syllogeous 49:15–49.

Harrison, P. 1984. Population, climate and future food supply. Ambio 13(3):161–167.

Heagle, A.S., W.W. Heck, J.O. Rawlings, and R.B. Philbeck. 1983. Effects of chronic doses of O_3 and sulfur dioxide on injury and yield of soybeans in open-top field chambers. Crop Sci. 23:1184.

Heck, W.W., R.M. Adams, W.W. Cure, A.S. Heagle, H.E. Heggestad, R.J. Kohut, L.W. Kress, J.O. Rawlings, and O.C. Taylor.

1983. A reassessment of crop loss from ozone. Environ. Sci. Technol. 17:573A-581A.

Irving, P.M. 1983. Acid precipitation effects on crops: A review and analysis of research. J. Environ. Qual. 12:442-453.

Kettunen, L., J. Mukula, V. Pohjonen, O. Rantanen, and U. Varjo. 1988. The effects of climatic variations on agriculture in Finland. p. 511-614. *In* M.L. Parry et al. (ed.) The impact of climatic variations on agriculture. Vol. 1. Assessment in cool temperature and cold regions. Reidel Publ. Co., Dordrecht.

Kimball, B.A. 1983. Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. Agron. J. 75:779-788.

Kimball, B.A., S.B. Idso, M.G. Anderson, and J.R. Mauney. 1987. Interactive effects of CO_2 and temperature on plant growth. p. 14. *In* Agronomy abstracts. ASA, Madison, WI.

Kramer, P.J. 1981. Carbon dioxide concentration, photosynthesis, and dry matter production. BioScience 31(1):29-33.

Lamb, J.J. 1986. The state-of-the-art review of the development of climatic scenarios. Task Force Meeting on Policy Oriented Assessment of Impact of Climatic Variations, International Institute of Applied Systems Analysis (IIASA), Laxenburg.

Land Evaluation Group. 1985. Socio-economic assessment of the implications of climatic change for food production in Ontario. Publ. LEG-22. Univ. School of Rural Planning and Development, Univ. of Guelph, Ontario.

Land Evaluation Group. 1986. Implications of climatic change and variability for Ontario's agri-food sector. Publ. LEG-26. Univ. School of Rural Planning and Development, Univ. of Guelph, Ontario.

Lemon, E.R. (ed.). 1983. CO_2 and plants: The response of plants to rising levels of atmospheric carbon dioxide. Westview Press, Boulder, CO.

Liverman, D.M. 1986. The response of a global food model to possible climate changes: A sensitivity analysis. J. Climatol. 6:355-373.

Lough, J.M., T.M.L. Wigley, and J.P. Palutikof. 1983. Climate and climate impact scenarios for Europe in a warmer world. J. Clim. Appl. Meteorol. 22:1673-1684.

Ludlow, L., and B. Smit. 1987. Assessing the implications of environmental change for agricultural production: The case of acid rain in Ontario, Canada. J. Environ. Manage. 25:27-44.

National Defense University. 1978. Climate change to the year 2000, A survey of expert opinion. Research Directorate of the Natl. Defense Univ., Fort Lesley J. McNair, Washington, DC.

National Defense University. 1980. Crop yields and climate change to the year 2000. Rep. on the Second Phase of a Climate Impact Assessment, Research Directorate of the Natl. Defense Univ., Fort Lesley J. McNair, Washington, DC.

National Defense University. 1983. World grain economy and climate change to the year 2000: Implications for policy. Rep. on the Final Phase of a Climate Impact Assessment, Research Directorate of the Natl. Defense Univ., Fort Lesley J. McNair, Washington, DC.

National Research Council. 1982. Carbon dioxide and climate: A second assessment. Rep. of the CO_2/Climate Review Panel. National Academy Press, Washington, DC.

Newman, J.E. 1980. Climate change impacts on the growing season of the North American Corn Belt. Biometeorology 7:128-142.

Oram, P.A. 1985. Sensitivity of agricultural production to climatic change. Clim. Change 7:129-152.

Palutikof, J., T.M.L. Wigley, and G. Farmer. 1984. The impact of CO_2-induced climatic change on crop yields in England and Wales. Prog. Biometeorol. 3:320-334.

Parry, M.L. 1978. Climatic change, agriculture and settlement. William Dawson and Sons, Folkestone, Kent, UK.

Parry, M.L., and T.R. Carter. 1988. The assessment of effects of climatic variations on agriculture: Aims, methods and summary of results. p. 11-95. *In* M.L. Parry et al. (ed.) The impact of climatic variations on agriculture. Vol. 1. Assessment in cool temperate and cold regions. Reidel Publ. Co., Dordrecht.

Parry, M.L., T.R. Carter, and N.T. Konijn. 1985. Climatic change. How vulnerable is agriculture? Environment 27:4-5.

Pitovranov, S.E., V. Iakimets, V.I. Kiselev, and O.D. Sirotenko. 1988. The effects of climatic variations on agriculture in the subarctic zone of the USSR. p. 615-722. *In* M.L. Parry et al. (ed.) The impact of climatic variations on agriculture. Vol. 1. Assessment in cool temperate and cold regions. Reidel Publ. Co., Dordrecht.

Pittock, A.B., and H.A. Nix. 1986. The effect of changing climate on Australian biomass production—A preliminary study. Clim. Change 8(3):243-255.

Postel, S. 1986. Altering the earth's chemistry: Assessing the risks. Worldwatch Pap. 71. Worldwatch Institute, Washington, DC.

Prior, S.A., H.H. Rogers, and N. Sionit. 1987. Water relations and growth responses of soybean in carbon dioxide-enriched atmospheres. p. 16. *In* Agronomy abstracts. ASA, Madison, WI.

Ramirez, J., C. Sakamoto, and R. Jensen. 1975. Agricultural implications of climatic change. p. 4-37-4-90. *In* Climatic Impacts Assessment Project (CIAP), Impacts of climatic change on the biosphere. U.S. Dep. of Transportation, Washington, DC.

Rogers, H.H., G.E. Bingham, J.D. Cure, J.M. Smith, and K.A. Surano. 1983. Responses of selected plant species to elevated carbon dioxide in the field. J. Environ. Qual. 12:569-574.

Rosenberg, N.J. 1981. The increasing CO_2 concentration in the atmosphere and its implications on agricultural productivity. I. Effects on photosynthesis, transpiration and water use efficiency. Clim. Change 3:265-279.

Rosenberg, N.J. 1982. The increasing CO_2 concentrations in the atmosphere and its implications on agricultural productivity. II. Effect through CO_2-induced climate change. Clim. Change 4:239-254.

Rosenzweig, C. 1985. Potential CO_2-induced climatic effects on North American wheat producing regions. Clim. Change. 7:367-389.

Santer, B. 1984. The impacts of a CO_2-induced climatic change on the agricultural sector of the European communities. *In* H. Meinl et al. (ed.) Socioeconomic impacts of climatic changes due to a doubling of atmospheric CO_2 content. Commission of the European Communities Contract no. CLI-063-D. Dornier-System, Friedrichshafen.

Santer, B. 1985. The use of general circulation models in climatic impact analysis—A preliminary study of the impacts of a CO_2-induced climatic change on Western European agriculture. Clim. Change 7:71-93.

Schlesinger, M.E., and J.F.B. Mitchell. 1985. Model projections of equilibrium response to increased CO_2 concentration. p. 81-148. *In* M.C. MacCracken and F.M. Luther (ed.) Projecting the climatic effects of increased CO_2. DOE/ER-0237. U.S. Dep. of Energy, Washington, DC.

Sionit, N., B.R. Strain, and E.P. Flint. 1987. Interaction of temperature and CO_2 enrichment on soybean: Photosynthesis and seed yield. Can. J. Plant Sci. 67:629-636.

Stewart, T.R., and M.H. Glantz. 1985. Expert judgement and climate forecasting: A methodological critique of 'Climate change to the year 2000'. Clim. Change 7:159-183.

Terjung, W.H., J.T. Hayes, P.A. O'Rourke, and P.E. Todhunter. 1984a. Yield responses of crops to changes in environment and management practices: Model sensitivity analysis. I. Maize. Int. J. Biometeorol. 28:261-278.

Terjung, W.H., J.T. Hayes, P.A. O'Rourke, and P.E. Todhunter. 1984b. Yield responses of crops to changes in environment and management practices: Model sensitivity analysis. II. Rice, wheat, and potato. Int. J. Biometeorol. 28:279-292.

Waggoner, P.E. 1983. Agriculture and a climate changed by more carbon dioxide. p. 383-418. *In* National Research Council, Changing climate. Rep. of the Carbon Dioxide Committee, Board of Atmospheric Sciences and Climate. National Academy Press, Washington, DC.

Waterstone, M. 1985. The equity aspect of carbon dioxide-induced climate change. Geoforum 16(3):301-306.

Williams, G.D.V. 1985. Estimated bioresource sensitivity to climatic change in Alberta, Canada. Clim. Change 7:55-69.

Williams, G.D.V., R.A. Fautley, K.H. Jones, R.B. Stewart, and E.E. Wheaton. 1988. Estimating effects of climatic change on agriculture in Saskatchewan, Canada. p. 219-379. *In* M.L. Parry et al. (ed.) The impact of climatic variations on agriculture. Vol. 1. Assessment in cool temperate and cold regions. Reidel Publ. Co., Dordrecht.

Yoshino, M.M., T. Horie, H. Seino, H. Tsujii, T. Uchijima, and Z. Uchijima. 1988. The effects of climatic variations on agriculture in Japan. p. 723-868. *In* M.L. Parry et al. (ed.) The impact of climatic variations on agriculture. Vol. 1. Assessment in cool temperate and cold regions. Reidel Publ. Co., Dordrecht.

ASSESSING THE IMPLICATIONS OF CHANGES IN CARBON DIOXIDE CONCENTRATIONS AND CLIMATE FOR AGRICULTURE IN THE UNITED STATES

Daniel J. Dudek

Senior Economist
Environmental Defense Fund
New York, New York

Abstract

This paper describes and demonstrates a methodology for the assessment of effects upon agriculture stemming from the accumulation of radiatively active trace gases in the atmosphere. Changes affecting agricultural productivity include the increase in atmospheric concentration of carbon dioxide and climate changes. The consequences of each of these effects are analyzed separately and and in combination to illustrate the importance of a comprehensive evaluation. The analysis also demonstrates the role of adjustments induced by a market economy in reallocating resources in response to environmental changes. Particular emphasis is placed upon assessing changes in both dryland and irrigated crop acreages as well irrigation water use. The implications for further research and policy are drawn in conclusion.

Environmental Change Effects on Agricultural Productivity

As one of the most weather sensitive sectors of our economy, agriculture is expected to be profoundly affected by climate changes. However, climate change is only one dimension of the range of impacts that agriculture is expected to face from the collection of environmental changes known as the greenhouse effect. The accumulation of several trace gases in the lower atmosphere that are radiatively active absorbing infrared radiation is the cause of this effect. Some of these gases, for example chlorofluorocarbons are implicated in stratospheric ozone depletion which has other severe environmental consequences. Increased ultraviolet radiation from a reduced ozone layer would directly reduce crop productivity (Teramura, 1986). Increased smog would also be produced with detrimental effects on crops (Heck, *et. al.*, 1983).

Other trace gases, for example carbon dioxide, have beneficial direct effects upon plant productivity (Strain and Cure, 1985). The atmospheric concentration of CO_2 effectively limits photosynthetic processes and therefore ultimate crop productivity. Increasing the concentration raises this limit and increases productivity, an inadvertent fertilization. Many of the activities producing these CO_2 increases also produce other atmospheric emissions such as ambient ozone precursors which have deleterious effects on plants. For a more complete discussion of the range of interrelationships and impacts between economic activity, environmental changes, and agricultural productivity see Dudek (1987b).

It is well known that the fortunes of the agricultural sector are highly weather dependent. While accommodating to temperature, precipitation, and storm variability are a common occupation in agriculture, the contemporary industry has not had to contend with actual climatic change. Such changes are anticipated to include increased temperatures, different precipitation patterns, altered evapotranspiration, and changed frequency and intensity of storm events. Large scale computer models of the earth's atmosphere and climate, termed general circulation models (GCM's), are the primary means by which such changes are predicted. While a variety of GCM's exist, one scenario from only one such model, the Goddard Institute of Space Studies' (GISS) GCM, is employed in this analysis. GCM's require the specification of expected trace gas emissions over time producing a scenario which describes climate changes as a result. A frequently analyzed scenario, also assessed in this paper, is the path to an atmosphere in which the concentration of CO_2 has doubled.

The GISS GCM has a spatial resolution of either 8 degrees latitude by 10 degrees longitude or 4 degrees by 5 degrees depending upon analytical needs (Hansen, et. al., 1983). Results on an 8 x 10 basis have been used in the research reported in this paper. The model simulates climate by solving the fundamental equations for conservation of mass, momentum, energy, and water. The GISS GCM has an equilibrium global mean sensitivity of 4.2 degrees Celsius for doubled CO_2 (Hansen, et. al., 1984). The doubling scenario results employed in this analysis assume continued growth in trace gas emissions. Consequently, no account is taken of the effect of the recent Montreal protocol upon chlorofluorocarbon emissions. The GISS GCM simulation experiments and results are described in Hansen, et. al. (1986).

The degree of correspondence between the 8 x 10 grid boxes for which GCM results are produced and state boundaries varies with the size of state. For example, grid box 1707 covers most of California and Nevada. In this research, GCM model resolution and the spatial scale for agricultural modeling were roughly matched. Table 1 presents GISS GCM results for temperature and evapotranspiration changes under a doubled CO_2 atmosphere. These climatic changes are reported for the agricultural production regions employed in this study (see Figure 1). The Northeast region at 3.7 degrees C increase shows the smallest change, while the Corn Belt and Delta States regions are predicted to experience the greatest rise at 5.3 degrees C. Evapotranspiration changes are much more ranging from 22% increases in Washington and Montana to only 1% in California and Nevada. However, the significance of these changes for agriculture can only be determined after analysis of their biologic and economic significance.

Assessment Methodology

A variety of approaches to the problem of evaluating the impact of climate change upon agriculture have been pursued. Basically, these studies follow two distinct lines. One approach is typified by the evaluation of historic events in the search for analogs as an aid in understanding response to change. The other line employs detailed computer studies of agricultural systems. The research reported in this study follows the latter approach as the more common method employed to assess the consequences of environmental changes. Computer studies of production response proliferated as economists attempted to analyze environmental problems like salinity, ozone, and acid deposition.

The general approach is to translate environmental changes into biologic responses which can be converted into productivity effects (Wetzstein, 1985). Crop responses, i.e. changed yields, are only one element of the ultimate effect upon farm firm revenues. Productivity changes affect supply response, i.e. the willingness of farmers to produce crops at different prices. Since many agricultural commodities, e.g. wheat, are produced in many locations across the nation in competition for the same customers, these individual effects must be aggregated. Prices for these commodities are determined by the interaction of both supply and demand. Consequently, the effects of market forces in reallocating resources and crops in response to productivity changes must be assessed.

Biologic response models have dramatically improved in recent years, progressing from statistical analysis of experimental data to highly detailed crop growth simulation models (Ritchie, 1984). However ideal, the latter tools are expensive to generate and operate. As a result, only a few crops have been modeled in this detail. Further, since the research reported in this paper is designed to produce an estimate of the relative impact of climate change, crop growth simulators are more precise than warranted. Consequently, general response assessments culled from existing literature have been employed.

Bolin, et. al. (1986) indicate a 10-50% increase in yields for C3 type crops in response to doubled CO_2. C3 type crops, barley, cotton, oats, rice, soybeans, and wheat in this study, are more efficient photosynthesizers than plants in the C4 category. C4 crops, such as sorghum and corn, would only have increases from 0-10%. Midpoints of the C3 and C4 ranges of 30% and 5% respectively were assumed for the direct CO_2 enhancement analyzed in this study. Estimates of climate change effects upon yields, particularly temperature, were drawn from the same source. The review by Bolin, et. al. concluded that yield reductions in the 3-17% range would result from a 2 degree C warming. A midpoint 5% yield decrement per degree C temperature rise was assumed for all crops for this study.

While the CO_2 and temperature effects identified above can be expected to potentially affect land resources devoted to agriculture, other resource use effects are important as well. Changes in the rates of evapotranspiration, identified regionally in Table 1, would affect both regional hydrology as well as irrigation demand (Rind and Lebedeff, 1984). The evapotranspirational changes from Table 1 were combined with Soil Conservation Service (1976) estimates of crop and location specific evapotranspiration rates to produce estimates of irrigation water requirements under the simulated climate change.

While precipitation predictions are available from the GISS GCM as well, several considerations militate against their use. First, the precipitation changes are the most uncertain of the parameters simulated. Second, the difficulty of translating precipitation changes into effective water supplies, both in surface impoundments and in groundwater aquifers, is beyond the scope of this effort. Lastly, the "snapshot" nature of this assessment does not consider changes in resource availabilities over time. On-going assessments are evaluating the implications of water supply changes (Dudek, 1987a). The current study evaluates changes in irrigation

TABLE 1. Temperature and Evapotranspirational Changes by Region

PRODUCTION REGION	TEMPERATURE CHANGE (degrees Celsius)	EVAPOTRANSPIRATIONAL CHANGE (percent)
Appalachia	3.9	9
Arizona	4.9	5
California	4.4	1
Corn Belt	5.3	7
Colorado	4.9	5
Delta States	5.3	7
Idaho	4.8	20
Kansas	4.6	9
Lake States	4.7	12
Montana	4.8	22
Nebraska	4.9	3
North Dakota	4.5	14
New Mexico	4.9	5
Northeast	3.7	2
Nevada	4.4	1
Oregon	5.0	15
Oklahoma	4.6	9
South Dakota	4.9	3
Southeast	3.9	9
Texas	4.3	11
Utah	4.9	5
Washington	3.9	22
Wyoming	4.8	20

Sources: GISS GCM temperature changes for doubled CO_2 were supplied by the U.S. Environmental Protection Agency's Office of Policy, Planning, and Evaluation to participants in the Symposium on Climate Change in the Southern United States. Evapotranspirational changes from the GISS GCM were taken from Rind and Lebedeff (1984).

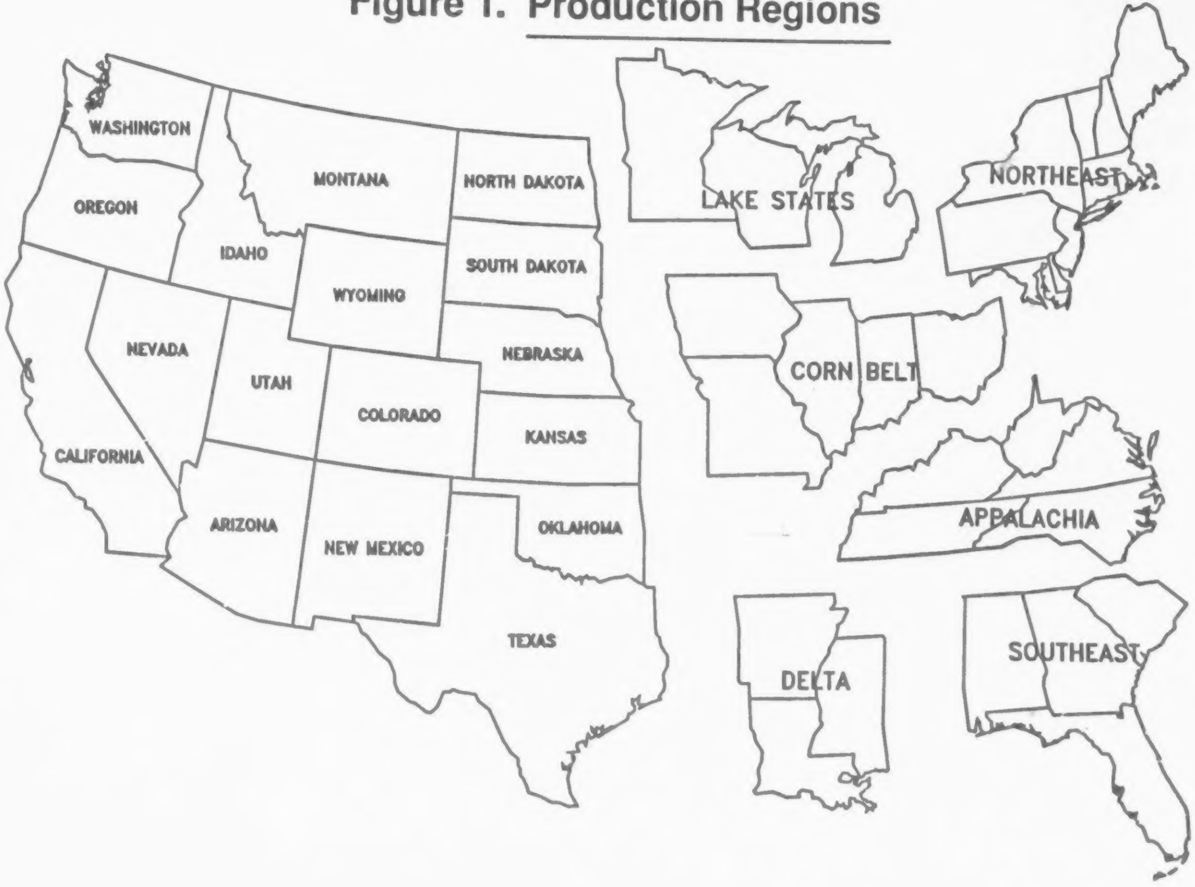
demand only against existing, developed water supplies.

This research differs from previous analyses (see for example Rosenzweig (1985)) of the effects of climate change upon agriculture in the use of a national agricultural model. The Western Resources Model (WRM), emphasizing greater spatial detail for the 17 western irrigated states, is derived from the model reported by Horner, et. al. (1985). The individual agricultural production regions represented within the WRM are displayed in Figure 1. Each of the 17 western states is separately modeled, while eastern U.S. agriculture is represented by 6 aggregated production regions. This difference in spatial detail within the model reflects the study's hypothesis that irrigated regions, despite their high degree of management control over water inputs, are likely to be more sensitive to climatic changes.

Crops included in the study include the principal grain and commodity program crops produced in the United States; barley, corn, cotton, oats, rice, sorghum, soybeans, and wheat. The WRM uses baseline information concerning resource availability, crop acreages, production costs, and resource use derived from published 1982 agricultural statistics. The structure of the model and data sources are more completely described in Dudek (1987c). However, fundamental changes in the dimensions and activities of the two models render the analysis reported in that paper uncomparable with the results from this model. The crop yield and resource requirement changes derived from the biologic and agronomic responses described above are translated into regional terms for analysis by the WRM.

Technically, the WRM is one of a class of quadratic programming models designed for agricultural analysis. Its main virtues are the simulation of market outcomes and spatial detail describing resource use. The WRM is a normative model which describes outcomes that "should" result from the scenario changes introduced into the model. However, the resulting outcomes should not be construed as forecasts, since no attempt has been made to forecast the myriad parameters required to portray the state of U.S. agriculture 40-70 years hence. Rather, the analysis presented is more aptly likened to a polaroid capturing a snapshot of the state of agriculture at one time under a specific set of circumstances. Dynamic economic models which would track the evolution of the agricultural system over time are currently very limited.

Figure 1. Production Regions


WASHINGTON
OREGON
CALIFORNIA
IDAHO
NEVADA
MONTANA
WYOMING
UTAH
ARIZONA
COLORADO
NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
LAKE STATES
CORN BELT
NORTHEAST
APPALACHIA
SOUTHEAST
DELTA

The WRM allocates resources and crop production among the regions given estimated climatic effects and resource supplies so as to maximize measures of producer and consumer welfare. The model allows supply response both in terms of changes in resource use as well as changes in the costs of production. For example, if groundwater is pumped in greater quantities, then the cost of pumping per acre-foot increases to reflect the greater depths from which the water would have to be withdrawn and greater energy use as well as the increased investment in wells and pumps. Land resource costs also vary in response to the intensity of cropland use. The inclusion of land conversion cost functions allows a more realistic appraisal of the effects of land use changes in response to environmental changes and economic forces.

It is important to emphasize the assumptions underlying the WRM. Current crop production technology is employed. As Decker, et. al. (1986) have noted, plant breeding has contributed significantly to the current high level of agricultural productivity and is likely to play a role in mitigating any adverse effects of climate change. No predictions concerning the efficacy of such future developments are included in this model. Further, as climatic change occurs around the global, international trade in agricultural commodities is likely to be altered. As Horner, et. al. have demonstrated, changes in export demand exert a powerful influence on agriculture and resource use. Current trade relationships only are assumed. Lastly, only the current stock of resource supplies are available for agricultural production. No further large scale development of water resources is anticipated.

Comparing Carbon Dioxide Concentration and Climate Change Impacts

The two major components of the changes associated with the greenhouse effect important for agriculture are changes in the ambient concentration of carbon dioxide and changes in climate. It has long been recognized that these changes are potentially significant for agriculture (National Defense University, 1980). Research concerning these agricultural implications has often focused on one set of effects or the other. Clearly, what is need is an assessment of the net effect of these changes on agricultural productivity. To illustrate the importance of assessing the net effect, this paper contrasts the results from focusing on a single set of effects in isolation with a combined analysis of all effects. An interesting by-product of this approach is a comparison of the relative magnitude of each of these effects when modeled separately.

The most immediate question concerning the impact of these changes concerns the total quantities of food and fiber produced, i.e. will supplies be adequate in current terms of reference? Figure 2 presents the equilibrium quantities of commodities produced and marketed under each of the scenarios analyzed. As anticipated from the assumptions defining crop response, crop production is increased under the CO_2 only scenario. The direct effect of CO_2 enhancement acts as free fertilization boosting output. However, production does not increase linearly by the 30% and 5% factors applied for C3 and C4 crops due to the moderating influence of market forces, i.e. the diminishing desirability of increasing quantities of food. The C4 crops, sorghum and corn, exhibit the least change.

The climate change scenario, analyzing only temperature and evapotranspirational changes, shows strong declines in production. Since the modeled effects are uniformly negative, this result is hardly surprising. Rice production, requiring between 2 to 6 acre-feet of water per acre, is reduced so sharply as a result of intense competition for available water supplies. Offsetting the productivity declines are increases in crop prices in response to reduced production and increases in the resources devoted to agriculture. Of particular note is the relatively greater magnitude of production effects under the climate change scenario when compared to the doubled CO_2 only result. Combining the two sets of effects produces more moderate absolute changes. Only corn and sorghum have relatively large reductions in production. As C4 crops benefit the least from the CO_2 enhancement, they are the least able to compete for more resources against other crops and their own cost structure.

To both economists and policy-makers, however, the adequacy question also has a price dimension. What will the impact of these be on consumers' food bills and how will farm income be affected? Figure 3 depicts the equilibrium prices predicted for the three alternative environmental scenarios analyzed. As expected, these outcomes display a pattern of changes directly opposite that for quantities. However, the percentage changes are much larger. For doubled CO_2, corn and sorghum prices drop the least since their production increased the least. Differences in crop price changes are due not only to differences in production changes, but also to differences in demand elasticities, i.e. the responsiveness of quantity changes to price changes. For example, under the climate change scenario, both rice and barley exhibit approximately the same percent reductions in production. However, as Figure 3

Figure 2. Aggregate Crop Production Changes

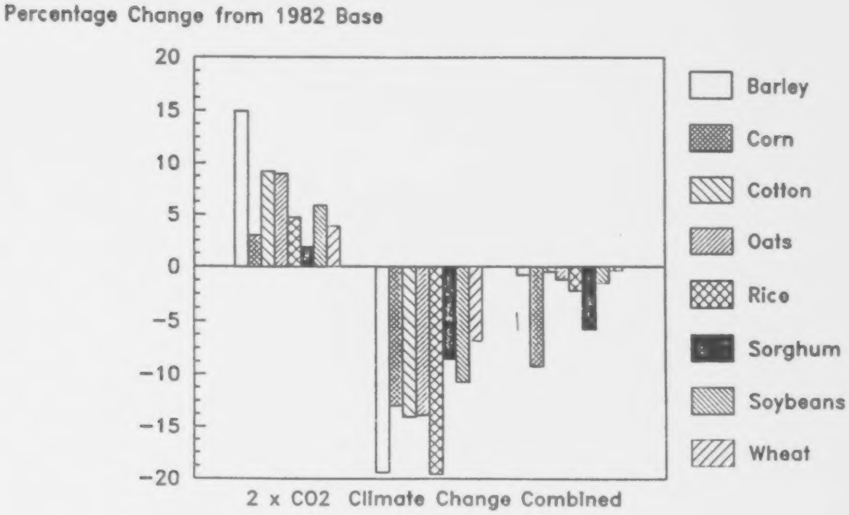
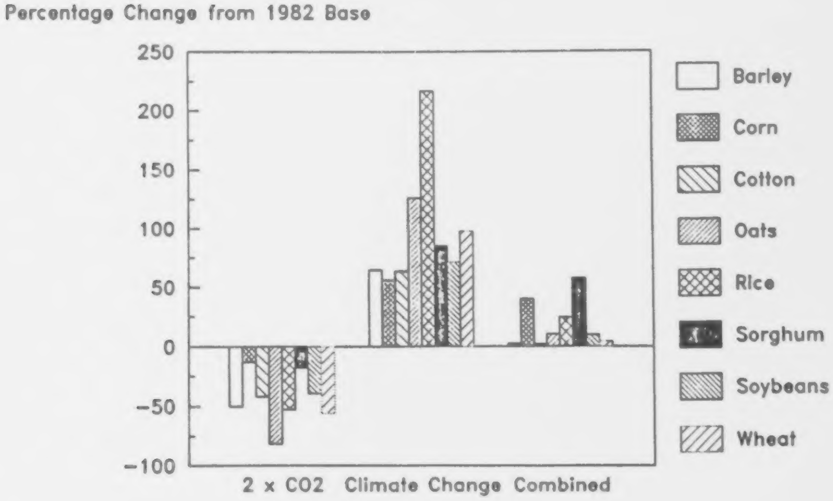


Figure 3. Aggregate Crop Price Changes



demonstrates, the corresponding price changes are markedly different. Barley's demand is more price elastic than that for rice.

As with production, relative price changes are much greater under the climate change scenario than under either of the alternatives. The combined scenario consistently shows the greatest effects on the C4 crops, sorghum and corn. These price changes help to underscore the distributional effects that can be expected under such widespread environmental change. In general, increased prices for agricultural commodities reduce consumer welfare while increasing revenues to agricultural producers. Net changes are complicated by our program of farm subsidies paid to producers from tax revenues levied on consumers. Consequently, increases in farm revenues should help to reduce the level of support payments, all other things being equal, providing a general benefit. However, distributional effects stemming from climate change can only be assessed from a regional perspective not afforded by the aggregate national market outcomes.

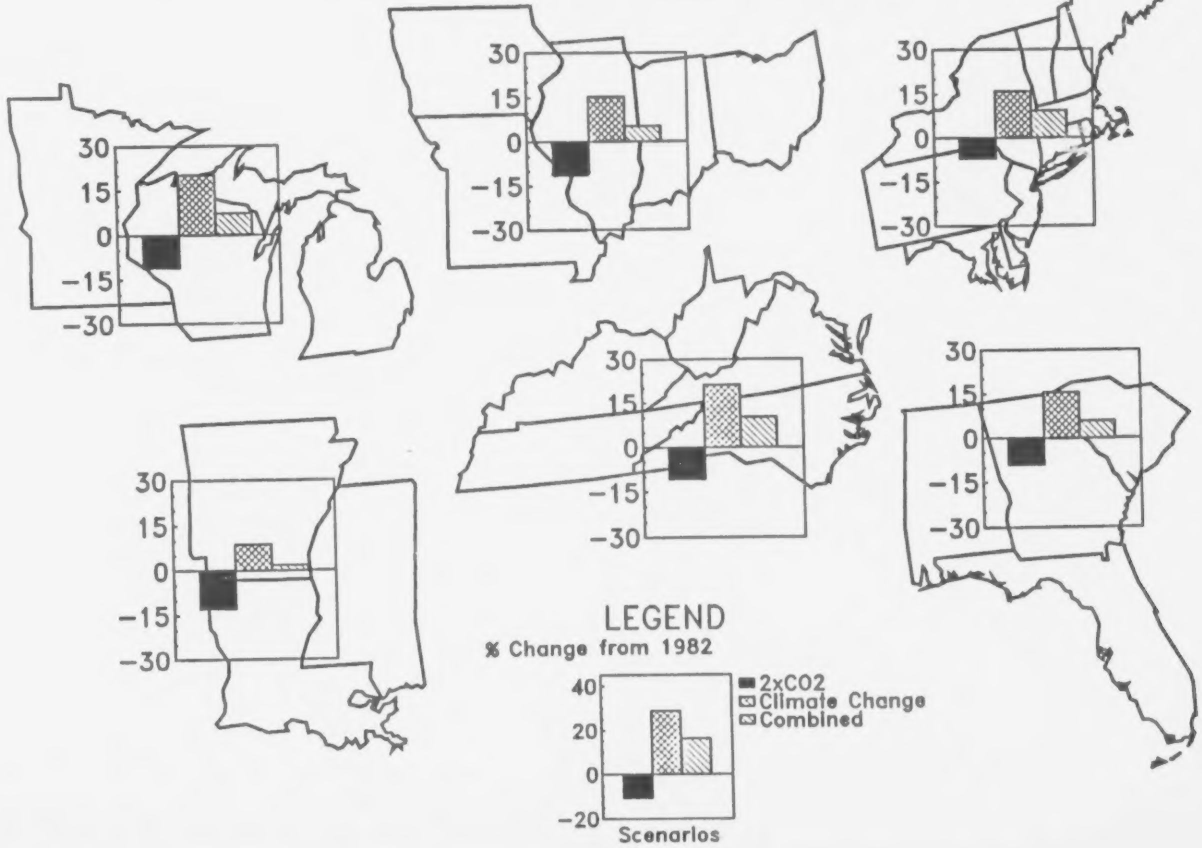
Most revealing of climate change impacts across the nation's agricultural economy is the effect upon regional resource use. In many regions of the country, agriculture exerts a powerful influence upon local, regional and state economies. It is also a significant determinant of local environmental quality as agricultural operations are the source of significant environmental insults. Since dryland and irrigated agricultural production are fundamentally different, varying in resource requirements, regional distribution, and response to climatic changes, they are presented separately. Readers may note some differences with previous assessments performed with this model (Dudek, 1987c). The major change is the introduction of nonlinear, i.e. price endogenous forms for all commodities. This version described in this paper runs on a VAX minicomputer while the former model runs on an AT-class personal computer with the usual limits on core memory.

Table 2 presents estimates of dryland crop acreage changes by region for each of the impact scenarios. The base 1982 dryland acreage stood at about 242 million acres for the nation as a whole. The fertilization effect of CO_2 is evident in the roughly 13% reduction in dryland acreage when that effect is assessed in isolation. Climate changes alone bring additional acres into production totaling 18% of base year acreage. Combining the two effects resulted in an overall 5.5% increase in dryland acreage. Regionally, the effects on dryland acreage are most pronounced in the eastern production regions. Figure 4 displays percentage changes in dryland acreages for

TABLE 2. Dryland Crop Acreage Changes by Region by Scenario

PRODUCTION REGION	1982 BASE	CO_2 ONLY	CLIMATE CHANGE	COMBINED
	******** millions of acres ************			
Appalachia	14.572	13.006	17.660	16.064
Arizona	0.016	0.013	0.019	0.017
California	0.801	0.715	0.894	0.815
Corn Belt	76.479	68.249	88.151	80.554
Colorado	3.102	2.450	3.818	3.158
Delta States	15.814	13.790	17.214	16.112
Idaho	1.362	1.106	1.591	1.398
Kansas	17.349	14.238	21.575	18.388
Lake States	26.740	23.783	32.158	28.705
Montana	6.642	5.219	7.987	6.764
Nebraska	9.122	8.133	10.513	9.614
North Dakota	14.146	11.107	17.289	14.625
New Mexico	0.623	0.533	0.745	0.648
Northeast	5.470	5.092	6.341	5.986
Nevada	0.012	0.009	0.013	0.012
Oregon	1.250	1.030	1.493	1.261
Oklahoma	7.970	6.775	9.481	8.144
South Dakota	9.898	8.423	12.183	10.500
Southeast	11.423	10.382	13.195	12.092
Texas	15.335	13.409	18.409	16.440
Utah	0.260	0.199	0.320	0.264
Washington	3.217	2.685	3.876	3.339
Wyoming	0.354	0.294	0.425	0.359
TOTAL	241.957	210.640	285.350	255.259

Figure 4. Eastern Dryland Crop Acreage Changes


30
15
0
−15
−30
LEGEND
% Change from 1982
40
20
0
−20
Scenarios
■ 2xCO2
▨ Climate Change
▨ Combined

each of the production regions and scenarios. Under the doubled CO_2 scenario, dryland acreage changes cluster around -10%. Climate change only effects are generally greater in absolute value, but not so uniform, however. For both the climate change and combined scenarios, the latitudinal gradient of effects predicted by the GISS GCM begins to be evident. All of the more northerly eastern production regions show greater sensitivity to climatic change. Actual acreage changes are greatest in the Corn Belt since its base acreage at 76.5 millions acres dwarfs all other regions. Even the seemingly modest 5% increase projected under the combined scenario translates into a whopping 3.8 million acre change.

Figures 5 and 6 display dryland acreage changes for the arid southwest and the pacific northwest. In each case, acreage changes for the doubled CO_2 only and climate change only scenarios were more nearly equal, although opposite in effect. The northern tier of southwestern states showed the strongest percentage changes of any of the regions in the West. Among the southwestern states, however, the largest absolute changes occurred in Kansas and Texas with approximately 1 million acre increases each under the combined scenario. The importance of comprehensive effects assessment is most in evidence in the dryland results for these western regions. Both of the single effect scenario produced strong directional changes in most of the regions. However, when combined in a single scenario, many of the individual regional percentage changes were below the national average of 5.5%.

Although only about 10% as large as total dryland acreage, irrigated cropland dominates many of the western production regions. For example, in this model, California had 0.8 million dryland acres, but over 3 million irrigated acres. Table 3 presents the base year's irrigated acreage and the irrigated acreage estimates for each of the scenarios. California, the Delta States, Nebraska, and Texas together account for about 60% of the nation's irrigated acreage. In the aggregate, the doubled CO_2 scenario resulted in a 12% decline in acreage from the base year. Climate change effects in isolation produced an overall 8% increase, while the effects combined produced a modest increase of 1.6%. Individual regional changes are portrayed in Figures 7 and 8.

Latitudinal gradients in the estimated effects are clearly in evidence from Figures 7 and 8. The production regions of the northwest show increased sensitivity and response under all of the scenarios analyzed. However, in each case, as throughout the West, the real issue is water. What is the implication of these irrigated acreage changes for water demand

Figure 5. Southwestern Dryland Crop Acreage Changes

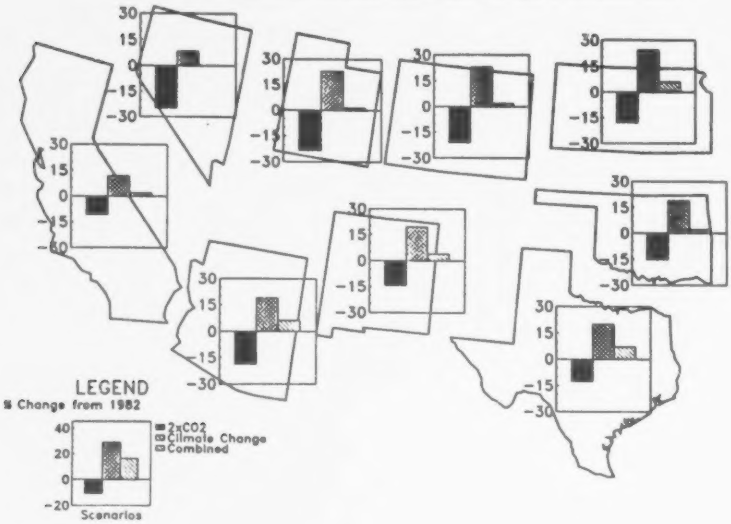

30
15
0
-15
-30
LEGEND
% Change from 1982
40
20
0
-20
Scenarios
2xCO2
Climate Change
Combined

Figure 6. Northwestern Dryland Crop Acreage Changes

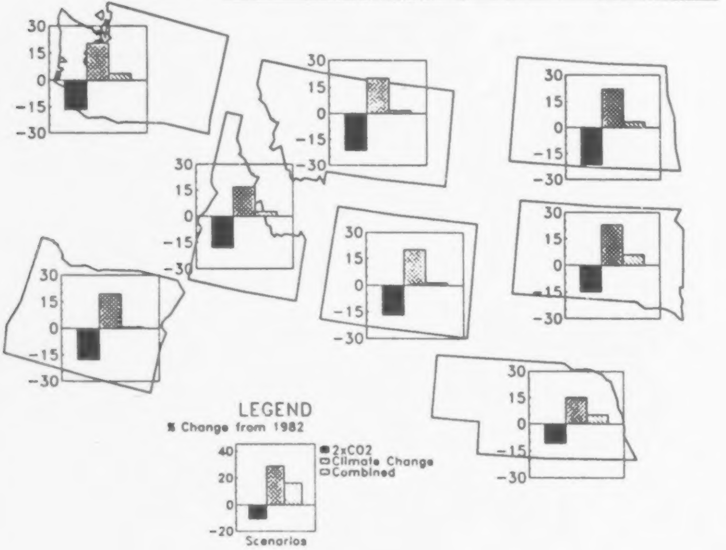

30
15
0
-15
-30
LEGEND
% Change from 1982
40
20
0
-20
Scenarios
2xCO2
Climate Change
Combined

TABLE 3. Irrigated Crop Acreage Changes by Region by Scenario

PRODUCTION REGION	1982 BASE	CO$_2$ ONLY	CLIMATE CHANGE	COMBINED
	******** millions of acres ************			
Arizona	0.668	0.615	0.720	0.669
California	3.249	2.866	3.697	3.373
Corn Belt	0.764	0.667	0.894	0.807
Colorado	1.211	1.085	1.396	1.290
Delta States	3.246	2.671	2.841	2.898
Idaho	1.365	1.149	1.554	1.365
Kansas	2.330	2.035	2.229	2.156
Montana	0.442	0.364	0.507	0.445
Nebraska	5.070	4.648	5.697	5.478
North Dakota	0.089	0.077	0.108	0.098
New Mexico	0.337	0.308	0.375	0.346
Nevada	0.049	0.041	0.056	0.050
Oregon	0.324	0.272	0.372	0.327
Oklahoma	0.332	0.294	0.381	0.341
South Dakota	0.237	0.218	0.268	0.252
Southeast	0.563	0.521	0.646	0.605
Texas	3.374	3.025	3.720	3.504
Utah	0.199	0.164	0.227	0.202
Washington	0.623	0.525	0.728	0.650
Wyoming	0.203	0.167	0.235	0.209
TOTAL	24.675	21.712	26.651	25.065

Figure 7. Southwestern Irrigated Crop Acreage Changes

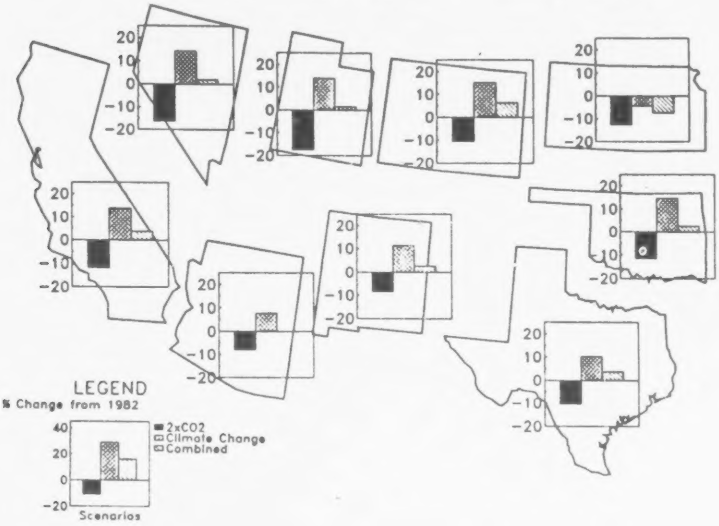
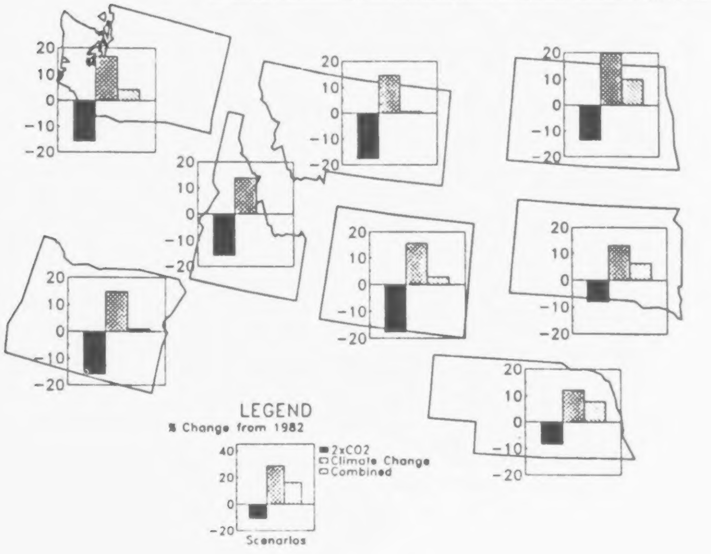

20
10
0
-10
-20
LEGEND
% Change from 1982
40
20
0
-20
Scenarios
2xCO2
Climate Change
Combined

Figure 8. Northwestern Irrigated Crop Acreage Changes


20
10
0
-10
-20
LEGEND
% Change from 1982
40
20
0
-20
Scenarios
2xCO2
Climate Change
Combined

and use? Table 4 lists the estimates of use for the base year and each of the scenarios. In the aggregate, these figures are in sharp contrast to the estimated acreage changes. These differences are due in large measure to the increases in evapotranspiration shown in Table 1. The CO_2 case results in a 12% reduction in irrigation water use. If only the climate change effects were analyzed, then irrigation water use would rise by 19.5%. The combined analysis of both sets of effects produces an 11.6% increase which is remarkably higher than the 1.6% underlying increase in irrigated acreage. In average per acre terms, applied water rates would rise from roughly 1.65 acre-feet per acre under the base and CO_2 scenarios to 1.82 acre-feet per acre for the climate change and combined cases.

Graphically and geographically, these changes are displayed in Figures 9 and 10. While for many of the preceding analyses the CO_2 and climate change effects seemed crudely balanced, they are clearly imbalanced when viewed in terms of the use of water resources. The climate change effects even when modulated by market forces clearly dominate the CO_2 enhancement. However, it must be emphasized that these results are based upon preliminary assessments of evapotranspiration changes and that no improvements in water use efficiency due to elevated CO_2 concentrations has been included. Each of these areas are active research topics. As these panels show, changes of 20% or more are not uncommon for many of the production regions. In a region already well-known for its strife over water, this magnitude of impact could be critical. At the least, it will stretch the capacity of water resource managers and perhaps cause us to rethink some of the archaic methods used to allocate water.

Water use and competition in the West are critical for environmental quality as well. Large segments of the national wild and scenic rivers system are in these affected regions. Can these investments survive this level of anticated increase in demand for irrigation water? Wildlife habitat is critically affected by agricultural operations both by the availability of riparian habitat as well as by the magnitue of water diversions. Finally, irrigation return flows, both surface and subsurface, are the conduit for many agrichemical and toxic residues. If the assumptions employed in this analysis are broadly correct, then we would expect one of the first manifestations of climate change impacts upon agriculture to be intensified water resource competition.

TABLE 4. Irrigation Water Use Changes by Region by Scenario

PRODUCTION REGION	1982 BASE	CO$_2$ ONLY	CLIMATE CHANGE	COMBINED
	******** millions of acre-feet *********			
Arizona	2.990	2.755	3.325	3.088
California	10.102	8.743	11.768	10.797
Corn Belt	0.522	0.456	0.703	0.631
Colorado	1.809	1.639	2.197	2.048
Delta States	5.061	4.103	5.062	5.062
Idaho	2.036	1.717	2.892	2.541
Kansas	3.038	2.697	3.139	3.139
Montana	0.591	0.489	0.833	0.731
Nebraska	5.304	4.872	6.286	6.080
North Dakota	0.083	0.071	0.119	0.107
New Mexico	0.626	0.575	0.729	0.676
Nevada	0.120	0.101	0.138	0.123
Oregon	0.561	0.475	0.721	0.635
Oklahoma	0.411	0.367	0.530	0.478
South Dakota	0.213	0.198	0.250	0.237
Southeast	0.335	0.312	0.458	0.432
Texas	4.970	4.507	6.769	6.297
Utah	0.385	0.318	0.456	0.405
Washington	1.178	1.011	1.625	1.465
Wyoming	0.408	0.334	0.547	0.485
	------	------	------	------
TOTAL	40.743	35.740	48.547	45.457

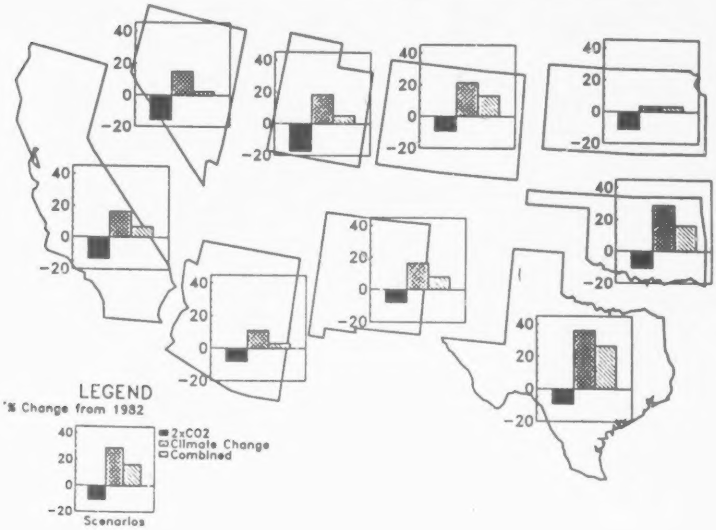


Figure 9. Southwestern Irrigation Water Use Changes

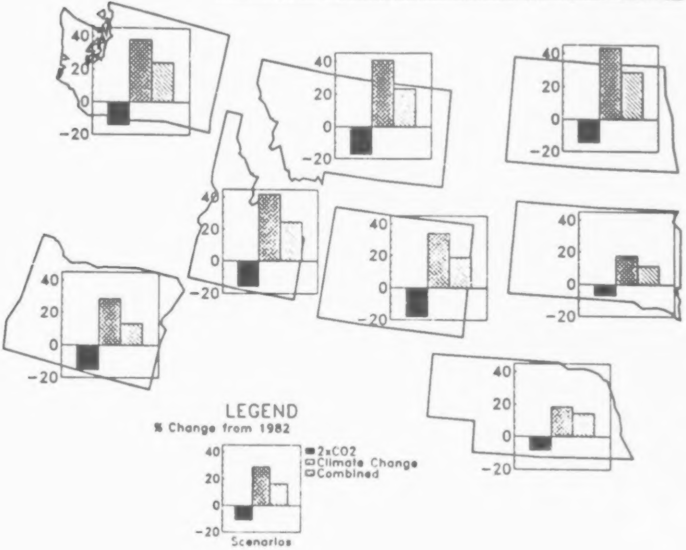


Figure 10. Northwestern Irrigation Water Use Changes

Conclusions

As indicated throughout, this research was intended to provide a broad estimate of the relative scope of climate change impacts upon agriculture. Defining a standard methodolgy for this assessment allows a greater focus on the assumptions employed rather than the methods. Several immediate research needs emerge. First, further refinements are needed in the specification of the impact of carbon dioxide concentration and climate changes upon individual crop productivities. In particular, these effects should be estimated with crop phenology models which include CO_2 enhancement. Similarly, while research has begun on the estimation of evapotranspirational changes, no scientific consensus exists. Even more urgent are improved regional precipitation and water supply impacts.

Not all improvements deal with the biologic response models. An important area of socio-economic inquiry is an investigation of the nature and costs of mitigating investments by individuals and society. One clear example that emerges form this research is changes in the institutional rules governing the allocation of water in many regions of the western United States. Water markets could be incorporated into national agricultural models to assess the impact of market forces upon resource allocation and use. These models could also introduce on-farm investment response to measure the trade-off between capital and improved irrigation efficiencies

At the macro level, we need to understand the future of agricultural programs with a particular view to subsidies and how changes in their design could provide offsetting forces. We require estimates of the effect of climate changes upon other important supply regions globally so as to evaluate possible changes in the size of the agricultural export market. Increased attention to the evaluation of changes in nonpoint source pollution loadings from agriculture as it adjusts in response to these global environmental changes is indicated. Lastly, we need to go beyond the simple aggregate arithmetic of national market outcomes to identify the types and direction of changes that are likely to be played out in response to climatic changes.

REFERENCES

Bolin, B., J. Jager, and B.R. Doos, "The Greenhouse Effect, Climatic Change, and Ecosystems: A Synthesis of Present Knowledge", B. Bolin, et. al. (editors), The Greenhouse Effect, Climatic Change, and Ecosystems, SCOPE 29, John Wiley & Sons, New York, 99. 1-32, 1986.

Decker, Wayne L., Vernon K. Jones, and Rao Achutuni, "The Impact of Climate Change from Increased Atmospheric Carbon Dioxide on American Agriculture", U.S. Department of Energy, DOE/NBB-0077, 100 pp., May 1986.

Dudek, Daniel J., "A Preproposal to Research Climate Change Impacts Upon Agriculture and Resources: A Case Study of California", Environmental Defense Fund, New York, 14 pp., May 1987a.

Dudek, Daniel J., "The Ecology of Agriculture, Environment, and Economy", background paper submitted to the Technical Workshop, "Developing Policies for Responding to Future Climatic Change", Villach, Austria, 25 pp., 28 September - 2 October, 1987b.

Dudek, Daniel J., "Economic Implications of Climate Change Impacts on Southern Agriculture", M. Meo (editor), Proceedings of the Symposium on Climate Change in the Southern United States: Future Impacts and Present Policy Issues, pp. 44-72, November 1987c.

Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis, "Efficient three-dimensional global models for climate studies, Models I and II", Mon. Wes. Rev. 111:609-62, 1983.

Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy, and J. Lerner, "Climate Sensitivity: analysis of feedback mechanisms", J.E. Hansen and T. Takahashi (editors), Climate Processes and Climate Sensitivity, American Geophysical Union, Washington, D.C., pp. 130-63, 1984.

Hansen, J., A. Lacis, D. Rind, G. Russell, I. Fung, P. Ashcraft, S. Lebedeff, R. Ruedy, and P. Stone, "The greenhouse effect: projections of global climate change", J.G. Titus (editor), Effects of Changes in Stratospheric Ozone and Global Climate, vol 1: Overview, pp. 199-218, October 1986.

Heck, W. W., et. al., "A Reassessment of Crop Loss from Ozone", Environmental Science and Technology, 17, pp. 573A-581A, 1983.

Horner, Gerald L. Putler and Susan E. Garifo, "The Role of Irrigated Agriculture in a Changing Export Market", ERS Staff Report AGES850328, Economic Research Service, USDA, 31 pp., June 1985.

Manabe, S. and R.T. Wetherald, "Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide", *Science*, 232:626-28, 1986.

National Defense University, *et. al.*, "Crop Yields and Climate Change to the Year 2000", Volume 1, report on the second phase of a climate impact assessment, Fort Lesley J. McNair, Washington, D.C., 128 pp., 1980.

Rind, David and Sergej Lebedeff, "Potential Climatic Impacts of Increasing Atmospheric CO_2 with Emphasis on Water Availability and Hydrology in the United States", U.S. Environmental Protection Agency, Strategic Studies Staff, Washington, D.C., 96 pp., April 1984.

Ritchie, J.T. and S. Otter, "CERES-Wheat -- A user-oriented wheat yield model", preliminary documentation, AGRISTARS publication no. YM-U3-044420JSC-18892, 1984.

Rosenzweig, Cynthia, "Potential CO_2 induced Climate Effects on North American Wheat-Producing regions," *Climate Change*, 7:367-89, 1985.

Soil Conservation Service, U.S. Department of Agriculture, "Crop Consumptive Irrigation Requirements and Irrigation Efficiency Coefficients for the U.S.", USDA, SCS, June 1976.

Strain, B.R. and J.D. Cure, editors, "Direct Effects of Increasing Carbon Dioxide on Vegetation", U.S. Department of Energy, DOE/ER-0238, 286 pp., December 1985.

Teramura, Alan H., "The Potential Consequences of Ozone Depletion Upon Global Agriculture", J.G. Titus (editor), *Effects of Changes in Stratospheric Ozone and Global Climate*, vol 2: Stratospheric Ozone, pp. 255-62, October 1986.

Wetzstein, Michael E., "Methods for Measuring the Economic Impact of Ambient Pollutants on the Agricultural Sector: Discussion", *American Journal of Agricultural Economics*, vol 67(2), pp. 419-20, May 1985.

STRATEGIES FOR ADAPTING AGRICULTURE TO ADAPT TO CLIMATE CHANGE

Stephen L. Rawlins, Director
Agricultural Systems Research Institute
Beltsville Agricultural Research Center
Beltsville, MD 20705

This paper is adapted from a more detailed analysis of food security strategies contained in a recently published paper by Dr. Martin Rogoff and myself (Rogoff and Rawlins, 1987).

A little background on how we became involved in this subject may be helpful. In the early 80's Martin and I had responsibilities for strategic planning for the Agricultural Research Service, first in the area of agricultural energy and then for the Agency as a whole. As members of the National Program Staff Martin had responsibility for biotechnology and I directed the natural resources program. One of the items in the 1977 Farm Bill we wrestled with was the designation of USDA as the "lead food agency". Our interpretation of this was that USDA had the responsibility for the Nation's food security, just as the Department of Defense has responsibility of the Nation's military security.

Our analysis revealed serious deficiencies. The human food chain is vulnerable in the long term. Normally we store little food compared to annual consumption. Storage of food products is difficult and expensive. But without more storage the carrying capacity of the food system is determined by the output of its worst production year. The existing US food chain could collapse as a result of one Fall without a harvest.

The US food system is highly dependent on weather, on fossil energy, and on other non-renewable inputs. If future weather patterns fluctuate as they have in the past, or if replacements for depleting fossil energy reserves are not found in time, the probability of experiencing a serious shortfall in food production in the next few hundred years appears almost certain. Add to this the potential for increased variability in rainfall and increased temperature that could result from carbon dioxide-induced climate change and we increase the vulnerability of our present food system. Our present food system depends on the successful completion of the flowering, pollination and seed formation each year for a very limited set, less than a handful, of crop species. Martin and I reasoned that something as critical as the human food supply needed more resiliency than this. Without alternative means of food production we are totally unprepared to cope with emergencies that could result from such things as climate change.

ANALYSIS OF THE PROBLEM

The source of all food energy is the sun. Through the process of photosynthesis in green leaves carbon from the atmosphere is reduced and combined with other elements to form sugar, from which all biomass is produced. The potential food energy captured in the form of biomass each year is hundreds of times more than the human population can now use. But much of it is the form of lignocellulose, which humans cannot digest. Our diet is derived primarily from seeds and other plant storage organs, or from animals, some of which can digest the more abundant cellulosic components of biomass.

The fact that our diet consists largely of plant seeds and storage organs makes it heavily dependent on annual crops. Annual crops expose the soil to erosion by wind and water. The natural perennial climax plant species that covered the land before it was cleared for agriculture maintained a protective organic mulch covering the soil. Soil erosion depletes not only the soil nutrients, but the loss of soil depth reduces the soil's capacity to absorb and store water between rains, increasing its vulnerability to drought.

Because annual crops are not naturally suited to the ecosystems in which they are grown, they require high inputs of agrichemicals, nutrients and fuel to produce adequate yields and to make them competitive with natural species. These inputs are dependent upon finite reserves of fossil fuels. Both soil erosion and depletion of fossil fuel reserves limit the sustainability of a food system based largely on the production of annual crops.

Our proposed alternative is based on the production of food from cellulose produced by wide range of perennial plant species that are adapted to natural ecosystems. A new crop, Kenaf, is one possibility, but tulip poplar or whatever fits the ecosystem best would be the crop of choice. The cellulose stored in these perennial plants represents a living reserve of feedstock for the food system that costs nothing to store. It need be harvested only when the demand for it exists. Producing food from the biomass of perennial species substantially increases the carrying capacity and sustainability of the food system. Its carrying capacity is increased in two ways; (1) by converting a much larger fraction of the annual solar energy flux captured in the form of biomass into human food, and (2) by eliminating the dependency of the food system on annual production. Its sustainability is increased by replacing annual crop species with perennial climax species that are more suited to the natural ecosystem, are less dependent on high inputs of fuel and chemicals from finite fossil fuel reserves, and which subject the soil to less erosion.

Producing food from lignocellulose consists of the following processes:

1. Biotechnological or chemical conversion to simple sugars for transportation as syrups to food production sites.

2. Chemical and biotechnological conversion of simple sugars to food or animal feed components, or to edible plant (or animal) organs in vitro at food consumption sites.

3. Conversion of food components to edible products as appropriate.

The basic strategy is to separate the set of processes concerned with carbon reduction, biomass synthesis and storage, which must be carried out in sunlight, from those concerned with the conversion of stored carbon into food, which don't require sunlight. Only this first set of processes is seasonally dependent. The second set, the conversion of stored polymers to simple sugar syrups at "the farm" site, transport and conversion of the syrups to food in "factories" near major population centers, can continue year round as dictated by demand.

We envision the same biological growth and biosynthetic processes that now convert photosynthate and polymers into food products in crop plants to be used to convert sugars into food products in food factories. The difference lies in the selectivity of the food factory processes to produce only edible material, as opposed to simultaneous biosynthesis of both edible and inedible plant parts by conventional crops.

Space does not permit a detailed outline of the conversion process here, but technically there appear to be no insurmountable barriers. The same biotechnology that is being pursued to enhance the productivity of crop plants in the field can be applied to enhance the growth of specific plant organs on sugar-based growth media indoors.

Let's take a look at what impact this alternative food system would have on the food we eat. First, grazing animals certainly would remain part of the system. These animals harvest and convert to human food a large amount of biomass that is too sparsely distributed to be feasibly harvested by other means. The increased dependence of the food system on natural ecosystems should enlarge the area available for grazing. Integrated forest livestock systems are already being used in many areas of the country. Wildlife and game production could also be enhanced by limited reforestation of some of our farm lands. (Reversing the deforestation trend by placing crop land back into perennial species would also provide a sink for atmospheric carbon dioxide.)

Chemical conversion of sugar to starch and other carbohydrate products could immediately provide feed for animals. Fish are very efficient converters of feed into food, and will be part of the biotechnical conversion process. The fact that the major portion of US agricultural land, most of the corn and soybeans, is devoted to the production of animal feed makes direct chemical conversion of sugar from biomass into animal feed a major contributor toward decreasing the demand for annual crops. Of course a sizeable fraction of the biomass could be harvested as forage to serve as a direct source of animal feed without first reducing it to sugar.

Poultry is also an efficient converter of feed to food, and can, like hogs, make use of waste products such as fish meal. Animals will be always be important in converting wastes to human food. A very large fraction of our existing food supply ends up as food waste that could be easily converted to food through animals if we developed the systems to recycle it.

No technological barriers seem to exist for developing products such as flour for bread or pasta, or a substitute for mashed potatoes directly from sugar. Specific proteins are now being produced in microbiological reactors, which could be used to supplement the diet. Since carbohydrate products are the backbone of the human food supply, it would appear that, combined with abundant animal products, a base food supply could be relatively easily achieved.

But ultimately we want more than meat and potatoes. Exciting new biotechnology is giving us the tools to produce specific plant organs indoors on culture media. Much of this effort is being devoted to cell culture to develop whole living plants from a single cell. But recent research is developing the capability to grow just part of the plant the same way. In one case cotton fibers are being grown without the rest of the cotton plant. Cherry fruit tissue has also been grown in a similar way. Other such products are waiting in the wings.

EXPLANATION OF KEY STRATEGIES

1. Primary plants grown in soil will be perennial, not annual.

Limiting plant production in soil to perennial field crops grown primarily in rainfed geographic areas has several major benefits. Soil will suffer less erosion; and both water and fossil energy will be spared by reducing the need for irrigation. With cellulosic materials comprising the major end product of soil based agriculture, living perennials can serve as an easily stored reserve of feedstocks. The fact that several year's supply of feedstock might exist in this reserve permits long-term contingency planning. Projected increases in food demand can be met simply by gradually expanding the area of this standing crop resource. In short, the annual yield of photosynthate can be stored, or harvested, as required. Non-crop cellulosic materials, previously useless as food other than through biotransformation by animals, become an emergency sump of reduced carbon for human food use. A hypothetical perennial hybrid with the attributes of tulip poplar, kenaf, and a nitrogen-fixing symbiont can be envisioned as the field crop of choice.

2. Bioconversion of standing stocks of reduced carbon to simple sugars with syrups as the main commodity produced from soil-based agriculture.

Processing of lignocellulose at the point of production allows by-products to be efficiently utilized. Practically everything, including the lignin, will either go into the conversion products or be used as fuel or fertilizer. "The farm" will be the primary point of food inventory control.

Only syrups will be transported to, and stored at, food production sites. In the existing system "food" moves into long-distance transportation channels involving refrigeration, cooling, controlled atmospheres, or other measures to protect it from spoilage. Technically the simplest means to move syrups is by pipeline. This is a low energy means of transport which requires no special steps for preservation at usual syrup concentrations. A demand-driven, year round harvest mode becomes possible. Syrup storage facilities at the food production site would only need capacity to balance minor fluctuations in supply and demand. Our present food system is supply-driven. Storage facilities must be large enough to carry the system from one harvest to the next. Year-round operations should significantly reduce the total size of unit processes including storage facilities, thus reducing overall capital investment. There will be no off seasons.

The primary source of energy for our food production facilities is natural sunlight captured on the farm and now converted to a sugar syrup stream. Waste disposal at the food production sites should be minimal since only edible plant parts, not whole plants, will be produced there.

Our scenario could significantly reduce the bulk of the existing system's current costs and problems. A spatially and temporally shortened marketing chain would reduce stored-product losses to pests, perhaps eliminating many of them. Also reduced or eliminated would be the cost for storage of raw food as mature or immature plant organs, e.g., seeds or seedbearing organs; long-term storage, e.g., freezing for raw or processed plant organs or parts; preservation processing, e.g., canning; packaging for long-term storage or long-distance transport; and processing of unripe harvested produce in transit or storage to ripen for market.

Food production in our alternative scenario is on-demand at demographically determined production sites in multipurpose facilities controlled by inventory-based systematics. Existing multipurpose, multisynthesis bioconversion or fermentation plants would seem to be reasonable models for these future systems.

3. Requiring only cellulose-rich plants for soil-based production, the alternate technology becomes relatively independent of climatic factors.

Barring cataclysmic continental natural disaster, e.g., nuclear winter, global axis shifts or total desertification, supply of cellulose is virtually assured. Even in extreme climates perennial floras can flourish. Localized early or late freezes, intermittent dry spells or excessive rainfall, may have disastrous effects on cropping systems whose products are annual plant organs or parts. Their effects on perennial crops grown for lignocellulose should be reversible by a following favorable season. Shifts in production loci, aside from social impacts, will simply shorten or lengthen syrup supply lines. Additional insurance the alternate technology provides is the potential of converting any cellulosic material to food, whether grown for the purpose or not.

POSSIBLE CONSTRAINTS

Assuming that the technologies we have envisioned are technically feasible, what other factors might stand in the way of achieving a secure food supply with this scenario? Four potential constraints are readily apparent; these are biomass availability, energy dependency, processing and delivery costs, and consumer acceptability of "high tech food".

1. Biomass Availability.

The alternate scenario proposes to reduce the dependency of food production on nonrenewable, resource-intensive agricultural production practices. This assumes that existing cellulose production capacity is adequate to generate the sugar feedstocks required for food. It is beyond this article's scope to analyze for preferred sites for biomass production under resource-conserving conditions. However, it is relatively simple to demonstrate that biomass availability will not prove to be a constraint.

Recent data indicate that the United States currently generates about 3.6 trillion pounds dry weight per annum of available lignocellulosic material, not counting that which ends up in agricultural end products. The available material includes wood chips, cereal straw, and cornstalks. Food consumption of major commodities in pounds retail weight for a 237 million population is 0.30 trillion pounds per annum. Two-thirds of this weight is made of high water-content products such as milk, meat, fruits, and vegetables. The other third includes grain, sugar, corn sweeteners and fats. Calculated annual US food consumption on a dry weight basis is, therefore, approximately 0.10 trillion pounds. On the basis of these numbers, the alternate food production technologies would required only 2.8 percent conversion efficiency of unused lignocellulose, or 7 percent conversion efficiency for its cellulose to provide all food consumed by the US population.

Use of these figures implies, correctly, that entry of the new technologies is foreseen as evolutionary, and that soil-based agriculture will continue at some level. Common sense, and the certain knowledge of consumer demand for specific "farm-produced" products dictate this assumption. The point, however, is that with current agricultural production providing over 30 times the necessary reduced carbon as waste, the acreage required for purposeful cellulose production is foreseen as relatively low. Conversion of only a small part of our highly productive agricultural land to the production of biomass would more than assure an adequate supply of food for the present population, leaving substantial arable reserve capacity for future population expansion. In short the feedstocks required should be renewable as long as energy flow from the sun is sufficient to maintain the carbon cycle.

2. Energy Dependency.

No quantitative energy analysis can be made for processes that do not exist. We can take a look in a general way at the energy budget of the current food system to see whether the new concepts provide any energy "surprises" which would negate its feasibility in terms of fossil fuel depletion.

It is abundantly clear that no one can convincingly argue that the existing food system can outlast our fossil fuel reserves. Our only hope for long term survival is to develop a food system substantially less dependent on fossil fuels.

The food system we have proposed is not radical in energy terms. We neither expect to create a new source of food energy, nor do we postulate a substitute for fossil fuel energy for success of our alternate food system.

What we propose to do is simply cycle a larger fraction of the annual carbon budget already being fixed in the leaves of growing plants through the human food chain. It appears that this fraction can be substantially increased, by at lease an order of magnitude. This eliminates the need to pour even more fossil energy into intensive annual crop culture to meet growing demand for food. The fixed carbon now wasted is largely recycled through microbial decomposition of organic residues. Routing a larger fraction of it through the human food chain would greatly relieve the pressure on the food system, and not perturb the balance of nature.

Even more important is the fact that our proposed scenario can reduce the currently high energy expenditure during food transfer and storage. The living reserve of standing perennial vegetation would cost little to maintain, and its potentially massive storage capacity would substantially raise the carrying capacity of the food system by removing the minimum year production limitation. It is the carrying capacity of the system that limits food security.

3. Economic Feasibility.

Traditional economic analysis is not very useful for long-term security issues, because no cost factors for a time 100 or more years from now can be projected realistically. One way to look at future economic feasibility is by comparison with the current food cost distribution at consumer level. The alternate technology cost distribution will be significantly different. By listing the estimated unit costs for the present system we can look at alternate technology unit operations, and project whether each new unit process could bear more or less cost. These unit costs are broadly divided into two operational categories, Farm Value and Market Bill. The latter represents the difference between payments to farmers for foodstuffs and consumer expenditures for these foods at food stores and eating places. It represented 72 cents of the consumer food dollar in 1982.

Analyses imply that reduced costs in the overall system could balance a sizeable increase in costs now incurred beyond the farm gate. Even if biotechnological food processing costs were to increase to double that in the present system, they imply that food cost to the consumer may not change.

What may be more important, however, is that whatever future comes to pass, whether extension of existing technology to 100-acre controlled environment domes, or the alternate technology, a massive infusion of new capital will be required. But new capital is scarce in the current food production, processing and distribution sectors. How to meet future capital demands needs to be a key issue in the future economic dialogue. Hopefully this time it will revolve around return on investment, not primarily on operating costs of production, as it has in the past. In short, there is little sense in agonizing over "economic feasibility" of new technology, when future parameters will actually control the costs.

4. Consumer Acceptability of New Technology Foods.

We do not propose to force future consumers to accept the next generation of ersatz coffee, and sawdust or algal bread. It is expected that plant growth in vitro will be held to the same quality standards as their current counterparts. We would even go so far as to project that certain products, e.g. soft drinks or preserves, which now rely on artificial flavorings, will be of better quality if prepared from plant tissues grown in vitro. We should detect no changes in our ketchup.

The challenge lies in developing technology to prepare high quality foods from singly-produced food components. Today we include textured soy proteins in certain foods, but the vegetarian veal cutlet has never generated broad consumer demand. This is due in part to the fact that consumers who want meat,want meat, but there is also a quality factor involved.

We do not deem the technical problem as insurmountable. There is great deal of research today attempting to define the basic determinants of food flavor and texture at the molecular level, and to determine the biochemical pathways involved in their formation. This applies to animal as well as plant-derived food products. For example, there is interest in overcoming the problem of "warmed-over flavor" in cooked beef, and "warmed-over texture" in pork. This is essential considering that single components of animal products should be no more difficult to produce biotechnologically than those from plant products. It is possible that culture of animal organs in vitro may require less time to attain than plant organs, since there is more basic knowledge of animal biochemistry and physiology than there is for plants.

There is even research emphasis now on unraveling the gustatory perception of smell. Success there would make an enormous contribution to the technology of fabricated foods.

We believe that significant inroads can be made initially by the new technologies, as they emerge, in the preparation of the carbohydrate polymer foods. One can readily visualize acceptable starchy foods in the pasta, bread and various dessert categories. Sauces are now fabricated products in this category. Dairy products would also appear a tempting target for these technologies.t There is no intent to stretch the technology's potential. We simply wish to point out that we believe the major diet items can be replaced by items produced by the new technologies without sacrifice of quality. It is the major diet items, primarily carbohydrates, on which food security is based. The condiments are trivia.

LITERATURE CITED

Rogoff, Martin H. and Stephen L. Rawlins, 1987. Food Security: A Technological Alternative. BIOSCIENCE 37:800-807.

CONTRIBUTIONS OF FORESTRY TO GLOBAL WARMING

(By Susan R. Fletcher, Specialist in Natural Resources Policy, Congressional Research Service)

Deforestation is occurring at a rapid rate in tropical regions. Tropical moist forests are often cut and burned to make way for very marginal agriculture or livestock ranches; in drier savannah areas, large numbers of people rely on fuelwood as their primary energy source. Although the data are poor on deforestation, and exact rates are not currently known, there is broad consensus that vast areas of forest are being lost. The readings in this section outline where deforestation is occurring, causes of deforestation, estimated rates of deforestation, and prospects for reforestation. Several of these selections emphasize the deforestation of the Brazilian Amazon because this area contains by far the largest concentration of moist tropical forests and because it is in Brazil that the most rapid deforestation is occurring.

The first selection, "Global View of a Tropical Disaster" by Sandra Postel, provides an overview of tropical deforestation and where it is occurring. The Department of Energy report that follows, "The Prospect of Solving the CO_2 Problem through Global Reforestation," provides extensive discussion of the areas where deforestation is occurring and trends in deforestation. In addition, this report, while addressing reforestation prospects, discusses both opportunities and limitations of this approach. One important factor in both the capacity and economics of forest use to mitigate global warming is the extent to which tree growth rates might be accelerated through species selection and cultivation practices. This factor is also treated in the DOE report, and in several papers in the next section.

The dynamics at work in deforestation and their relationships to the Earth's carbon cycle and global climate change are the subjects under discussion in the next three selections. In "A Green Fix to the Global Warm-up" by Sandra Postel, the role of trees in forests in the carbon cycle is described. The recent situation specifically in Brazil as revealed by reports over the past year is summarized in an August 1988 *New York Times* article, "Vast Amazon Fires, Manmade, Linked to Global Warming." Finally, another *New York Times* article, "Ambitious Amazon Expedition Probes Forest's Role in Global Atmosphere," describes a program of the National Aeronautics and Space Administration (NASA), and provides a perspective on the complicated feed-back systems that influence the chemistry of the forest in absorbing and emitting carbon dioxide.

The particular significance of Brazil's forests, the role of government policies in Brazil in exacerbating deforestation, and some approaches to dealing with the problem are the subject of the next three selections. First, "The Significance of the Amazon Basin for Global Climatic Equilibrium," by Peter Bunyard, discusses the role of moist tropical forests not only with respect to global warming but also in hydrological cycles that affect weather and climate. Two sections from Dennis Mahar's "Government Policies and Deforestation in Brazil's Amazon Region," discuss incentives to development and settlement activities that cause deforestation, and concludes with some policy recommendations. Finally, a July 1988

New York Times article, "Plan for Amazon Backed in Brazil," identifies efforts under the auspices of the International Tropical Timber Organization (ITTO) to address and ameliorate deforestation.

Global View of a Tropical Disaster

Frans Lanting

Malagasy woman sells charcoal

*The natural systems of much of the developing world are coming apart at the roots as **40 million acres** of forests are destroyed each year, impoverishing people, the soil, the gene pool, and even our climate. Solutions require a truly global commitment.*

By SANDRA POSTEL

Sandra Postel is Vice President and Senior Researcher, Worldwatch Institute, and coauthored with Researcher Lori Heise Worldwatch Paper 83, Reforesting the Earth

Local logger eyes a Madagascar hardwood

Frans Lanting

With the simple ax, the mighty chainsaw, and all-powerful fire, humankind has chipped away at the earth's rich mantle over the centuries. Since settled agriculture began about 10,000 years ago, forests and woodlands have dwindled by nearly five billion acres—a third of the original total.

For many centuries, this shrinkage of forest cover hindered human progress little, if at all. Indeed, the clearing of trees to make way for cropland and pasture, and the harvesting of wood for fuel and timber, were vital to economic and social development.

But in recent decades, the scale and pace of deforestation have greatly accelerated. Each year 28 million acres of tropical forest are destroyed through the combined action of land clearing for crop production, fuelwood gathering, and cattle ranching. Commercial timber harvesting degrades at least an additional 11 million acres. All told, an area of trees slightly larger than New York

Millions of Third World people lack enough wood to cook meals and heat their homes.

and Vermont combined is lost or logged over each year.

This relentless loss of woodlands is now undermining the economic and environmental health of numerous nations, mostly in the developing world. Trees quite literally form the roots of many natural systems, and they are a vital component of the survival economy of the rural poor. As a result of deforestation, millions of people in the Third World lack enough wood to cook their meals and heat their homes. Soils are eroding. Plant and animal species are disappearing. And the release of carbon stored in forests is adding to the atmospheric pool of carbon dioxide, hastening the onset of CO_2-induced climate change, arguably the most threatening environmental problem of modern times.

A glance back through history shows that dramatic changes in a region's forest cover typically reflect powerful societal transformations. Beginning in the 16th century, for example, the expanding agricultural and industrial needs of Renaissance societies spurred the clearing of large tracts of forest in western Europe. France, once 80 percent forested, had trees covering only 14 percent of its territory by the late 18th century.

Similarly, forest cover in what is now the contiguous United States totaled 950 million acres in 1630, about when the Pilgrims arrived. As colonization spread along the eastern seaboard and gradually westward, forests dwindled. By 1920, trees covered 615 million acres, more than a third less than when European settlement began.

Today forest cover is fairly stable in most of the industrial countries; in some, it is even increasing. As these countries intensified their agricultural production and diversified their economies, the need for forest clearing diminished. About a quarter of France is now forested, up substantially from its historic low. Forested area in the United Kingdom has expanded an average of about 86,000 acres a year since the early '60s. And in the contiguous United States, forest cover has been fairly stable during most of this century, though it has declined over the last two decades as farmers plowed up more land to meet widening demands for exported grain.

In the developing world, however, the forces behind deforestation remain strong. The United Nations Food and Agriculture Organization (FAO) generated the first comprehensive survey of tropical forests in 1981. Its most worrisome finding: Trees were being cut much faster than nature or reforestation were replacing them. For tropical regions as a whole, 10 acres were being cleared for every one planted. In Africa, the ratio was 29 to one; in Asia, 5 to one.

Sadly, the picture is probably even bleaker than this. Recent satellite data show that some regions have been losing forests much faster than the FAO's figures suggest. Satellite pictures for the state of Rondonia in Brazil's Amazonian region show, for example, that 2.5 million acres of rich rainforest were cleared in that one state alone in 1984.

Populations Whose Fuelwood Supplies Cannot Be Sustained

	1980			2000
REGION	ACUTE SCARCITY[1]	DEFICIT[2]	TOTAL	ACUTE SCARCITY OR DEFICIT
	(millions of people)			
Tropical Africa	49	200	249	622
Tropical Asia[3]	29	710	739	1,434
Tropical America	18	143	161	342
Total	96	1,053	1,149	2,398

[1] Fuelwood consumption below that required to meet minimum needs.
[2] Minimum fuelwood needs are met, but only by overcutting and depleting wood resources.
[3] Does not include China.

Source: U.N. Food and Agriculture Organization, *Fuelwood Supplies in the Developing Countries*, Forestry Paper 42 (Rome, 1983).

T. M. Catterson

In a classic example of slash and burn agriculture, maize is planted in the fragile soils of a recently deforested hillside.

Logging in the Ivory Coast has contributed to halving of that nation's forested area in 20 years.

and 1985 (see the photos on page 58).

Likewise, remote sensing data reveal that India has been losing an average of 3.2 million acres each year, a rate nine times higher than FAO had estimated. The FAO has begun a second tropical forest inventory that will rely more heavily than the first one on satellite imagery, so a more accurate picture of forest cover and deforestation rates should be available in a few years.

The conversion of forest to cropland is by far the leading direct cause of deforestation in the tropics. Rapid population growth, inequitable land distribution, and the spreading of export agriculture have greatly reduced the area of land available for subsistence farming. Lacking alternatives, peasants clear virgin forest to grow food. Unfortunately, fragile tropical soils are often not suitable for continuous cultivation. The soils eventually become so depleted of nutrients that peasant colonists must clear more forests to survive.

Indigenous "shifting cultivators," on the other hand, follow a long tradition of clearing a field, cultivating it for a few years, and then moving to a new area while forest regrowth restores the original site's fertility. Many years later, they would return to the first plot to plant crops there again.

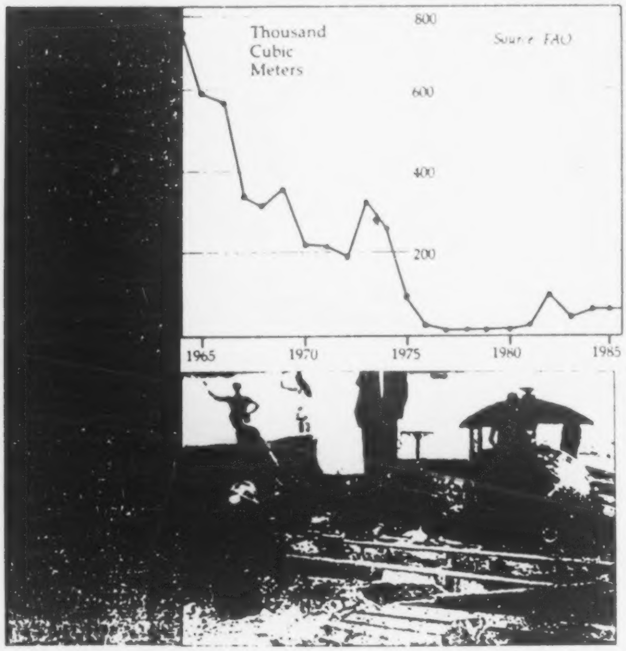
With the population buildup of recent times, this once sustainable practice has broken down. Farmers are forced to recultivate land before it has recovered, which over time leads to chronic land degradation. Indonesia alone has nearly 40 million acres of nonproductive land that will not support crops or forest without major rehabilitation.

Population pressures have in some areas turned fuelwood collection into an unsustainable practice as well. Given a choice, villagers usually gather dead wood and branches for fuel. They cut live wood only if nothing else is available or if they are converting wood to charcoal for urban markets.

Fuelwood gathering thus contributes to deforestation primarily in the arid woodlands of Africa, where population density is high and the natural growth rate of vegetation is low, and around cities in Asia and Africa, where concentrated demand outstrips the available tree stock. Recent satellite data show that in less than a decade, forest cover within 100 kilometers (62 miles) of India's major cities dropped by 15 percent or more; the area surrounding New Delhi lost a staggering 60 percent.

An additional agent of forest destruction has operated in Latin America: the lure of cattle ranching. Some 3.7 million acres of pasture had been established in Brazil's Amazonian region by the late '70s. Similarly, between 1961 and 1978, pasture in Central America expanded 53 percent while forests and woodlands declined 39 percent. Much of that conversion was driven by growing demands for cheap beef to supply fast-food chains and convenience food processors in the United States. U.S. demands played less of a role in Brazil, because U.S. law prohibited imports of frozen beef from countries plagued by foot and mouth disease.

Fortunately, the "hamburger connection" with Central America's forests has largely been broken. A dramatic decline in U.S. beef consumption, escalating tensions in El Salvador, and the U.S. trade embargo against Nicaragua combined to narrow the pipeline from Central American pastures to U.S. dinner tables during this decade. The re



Estimated Net Release of Carbon to the Atmosphere from Tropical Deforestation, 1980

COUNTRY	NET CARBON RELEASE[1]	SHARE OF TOTAL
	(million tons)	(percent)
Brazil	336	20
Indonesia	192	12
Colombia	123	7
Côte d'Ivoire	101	6
Thailand	95	6
Laos	85	5
Nigeria	60	4
Philippines	57	3
Burma	51	3
Peru	45	3
Ecuador	40	3
Vietnam	36	2
Zaire	35	2
Mexico	33	2
India	33	2
Others	337	20
Total	1,659	100

[1] Figures are midpoints of estimated ranges; the estimated total release from tropical deforestation in Houghton et al. ranges from 900 million to 2.5 billion tons.

Walt Anderson

Source: R.A. Houghton et al., "The Flux of Carbon from Terrestrial Ecosystems to the Atmosphere in 1980 Due to Changes in Land Use: Geographic distribution of the Global Flux," *Tellus*, February/April 1987.

gion's beef exports peaked in 1979 and by the mid-'80s had fallen by nearly two-thirds.

Industrial countries' appetite for tropical hardwoods also contributes to forest destruction. This ready market encourages Third World countries to "mine" their forests to earn vital foreign exchange. For example, Malaysia—currently the leading tropical log exporter—gets all of its export logs from the states of Sabah and Sarawak. The rate of timber harvesting in Sabah is four times the rate of natural regeneration, leading to forest depletion. Similarly, unsustainable logging in Cote D'Ivoire (Ivory Coast) has contributed to a halving of the nation's forested area over the last two decades. If this rate of destruction continues, the country's forests will be completely gone in 16 years.

Logging can theoretically be practiced sustainably, but more often it severely degrades forestland. As loggers selectively cut commercially valuable tree species—which typically account for less than 10 percent by volume of any given acre—they frequently destroy 30 to 60 percent of unwanted trees as well.

More than 500 million acres of tropical forest have been logged over so far, and that figure expands by some 11 million acres a year. To date, roughly two thirds of the logging has been done in Southeast Asia, but it will likely expand in Latin America and, eventually, Africa as Asian forests are depleted.

Commercial timber harvesting also fuels deforestation by opening virgin forests to landless colonizers. After timber companies build roads to enter and exploit a forest stand, peasant farmers use those roads to gain access to unclaimed land. They clear and burn the vegetation to plant subsistence crops, completing the deforestation cycle.

Finally, national governments and international lending agencies have fostered deforestation through their "development" projects. The World Bank, for example, has funded colonization schemes, road building, and the construction of large dams and reservoirs that have abetted the devastation of large tracts of forest. Such projects clearly involve tradeoffs, but often the environmental losses seem to have outweighed intended benefits, or the benefits have simply not been sustainable.

Indonesia's transmigration program is a case in point. Aided by more than $1 billion in World Bank funds, the Indonesian government has transported more than four million peasant farmers from the crowded islands of Bali and Java to the less-populated, heavily forested islands of the archipelago. The government's stated aims have been to relieve population pressures and to boost food production, though critics charge the project is intended to defuse political unrest on Java and establish a more loyal following in the culturally distinct outer islands.

Whatever the principal motive, the transmigration scheme has offered little hope of sustainable livelihoods for the incoming migrants, while sacrificing large areas of forest. Low crop yields on the nutrient-poor forest soils have made it hard for the resettled farmers to eke out a living. Half of them still live on poverty incomes of less than $360 a year. At the World Bank's urging, the Indonesian government has cut back the program and plans to use remaining funds to make existing resettlement sites more viable.

Several major consequences manifest at the local, regional, and global levels—arise from the ongoing loss of tree cover in the Third World. Deforest-

turn to page [illegible]

GLOBAL VIEW OF A TROPICAL DISASTER

continued from page 29

ation's inexorable march is worsening the lot of rural villagers, undermining national economies, extinguishing plant and animal species, and destabilizing the earth's climate. Without concerted efforts to protect the forests that remain and to plant more trees, there appears little hope of improving humanity's prospects.

More than two-thirds of all Third World people rely on wood for cooking and heating. Rural dwellers depend almost exclusively on wood, even in oil-rich Nigeria. As wood supplies dwindle, growing numbers face a deepening energy crisis.

The FAO estimated that in 1980 nearly 1.2 billion people in developing countries were meeting their fuelwood needs only by cutting wood faster than it was being replaced. Nearly 100 million people—half of them in tropical Africa—could not meet their minimum needs even by overcutting the woodlands around them. According to the FAO's projections, half the people in the developing world will lack a sustainable supply of fuelwood by 2000.

Yet the human and ecological costs of wood scarcity are already high. In rural parts of the Himalayas and sub-Saharan Africa, women and children spend 100 to 300 days a year gathering fuelwood, pulling them away from farming, education, and other productive activities. Boiling water becomes an unaffordable luxury, and quick-cooking tubers and cereals replace more nutritious but slower cooking foods such as beans.

Where fuelwood is critically scarce, people often have no choice but to divert dried dung and crop residues from fields to cookstoves, a practice that can reduce soil fertility and lower crop yields. In Nepal, this diversion reduces grain yields an estimated 15 percent.

In urban areas, where fuelwood is bought and sold in markets, scarcity leads to skyrocketing prices. Working-class families throughout the Third World typically spend 20 to 40 percent of their meager incomes to buy wood or charcoal—about the same share of earnings families in the U.S. spend on housing. Since the urban poor lack the option of turning to crop waste or dung, rising fuel prices mean reduced living standards.

Perhaps the most tangible of deforestation's economic effects are those caused by the unsustainable logging of tropical timber. In many areas, timber is being mined, much as gold, oil, and other nonrenewable resources are extracted. Nigeria, for example, was once among the world's largest tropical log exporters. But largely because of overexploitation of its forests, hardwood log exports declined from 773,000 cubic meters (27,600,000 square feet) in 1964 to a mere 60,000 (2,100,000 square feet) in recent years. The nation earned only $6 million from its exports of all forest products in 1985 and spent $160 million that year on forest product imports.

Similarly, in Ghana the volume of forest product exports dropped by two-thirds between 1974 and 1985. Though about 33 developing countries are currently net exporters of wood, that fig

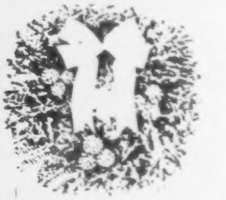
Charlton Heston for America's National Forests

"I REALLY LOVE THESE FORESTS."

The National Forests are such great places to unwind. The air is crisp and clear. The sky is a deep blue and everything you see fills your eye with pleasure.

These wonderful getaway places are open to everyone, and they are easy to reach ... a day's drive or less away from just about anywhere in America. To learn more write FORESTS FOR US, Box 2000, Washington, DC 20013. Then get ready to enjoy

FORESTS FOR US
FOREST SERVICE



TRADITIONALLY ELEGANT GIFT from the MAINE WOODS

Our Naturally Fragrant
Balsam Fir Wreath

Handcrafted from freshly gathered boughs, beautifully decorated with a big red bow, natural pine cones, shiny red berries. 22" diameter. Optional personalized gift card.

$19.95 Plus $3.00 shipping and handling

Business Gift Rates Available
Major Credit Cards Accepted

We also ship Christmas Trees, Centerpieces, Kissing Balls, Balsam Sachets, Cone Wreaths & other handcrafted Christmas specialties. Write for a free brochure.

Hall's Christmas Tree Farms
P.O. Box 45, Department H88
Dover-Foxcroft, Maine 04426

Why not save some time—call us toll-free today!
Out of state 1-800-447-1217 Ext. 111
in Maine 1-800-445-1225 Ext. 111

Destruction or Protection?

Future Directions for Tropical Rain Forests

The Tropical Rain Forest
A First Encounter
M. Jacobs, R.A.A. Oldeman,
R. Kruk,

Contents:

1988/311 pp./170 Illus./8 tables/hardcover $39.95
ISBN 0-387-17996-8

Amazonian Rain Forests
Ecosystem Disturbance and Recovery
Carl F. Jordan,

1987/133 pp./55 Illus./2 tables/hardcover $45.00
ISBN 0-387-96397-9

To order by credit card:

Or:

Springer-Verlag New York, Inc.

Springer-Verlag

ure may drop to around 20 in 10 years.

Though harder to quantify, the ecological consequences of deforestation entail real economic and social costs as well. India's Chipko movement, a nonviolent resistance campaign initiated to save trees in the Himalayas, promotes the slogan "What do the forests bear? Soil, water, and pure air." The motto reflects a growing awareness of the vital role forests play in stabilizing soils, conserving nutrients, and moderating water supplies. Unfortunately, in many parts of the Third World, these environmental services are being undermined at a rapid rate.

Just how much ecological disruption forest clearing causes depends on a number of factors, including topography, rainfall patterns, soil types, and how the land is used and treated following clearing. Generally, forests help anchor soils, so the loss of tree cover, especially from steeply sloping hillsides, can lead to large losses of topsoil. Besides diminishing upland productivity, such erosion transfers sediment to river channels, which aggravates local flooding and contributes to the premature silting of reservoirs downstream.

If deforestation is followed by overgrazing or poor crop production practices, as is often the case, soils compact and lose some of their ability to absorb rainwater. Water then tends to run over the land surface rather than soaking into the ground to replenish soil moisture and groundwater reserves. In regions of intense rainfall, this loss of the soil's absorption capacity can also increase flooding.

Perhaps nowhere are the worsening effects of flooding and siltation more evident than in South Asia. Researchers at the Centre for Science and Environment in New Delhi estimate that the flood-prone area in India now totals 145 million acres, more than double a government estimate for the late '60s of 62 million acres. At one monitoring point along the Brahmaputra River, the peak flood level rose an average of a foot per decade between 1913 and 1978. According to these researchers, "We are no longer dealing with disaster events but disaster processes."

While citizens of the Third World feel deforestation's effects most directly, people everywhere have a stake in tropical forests' fate. Tropical rain forests claim only seven percent of the earth's land surface, but they harbor more than half of all plant and animal species. Scientists have counted as many tree species on 25 acres in Borneo as exist in all of North America.

Deforestation has already destroyed the habitats of unknown numbers of plant and animal species, driving them to extinction. A fifth of all species now living could disappear during the next 15 years. *(For more details on animal and plant extinctions, and a ray of hope, see this magazine's FOCUS section, beginning on page 41.)*

One other global consequence looms large. Forests play a crucial role in the planet's cycling of carbon. Together vegetation and soils hold two trillion tons of carbon, roughly triple the amount stored in the atmosphere. When trees are cleared, the carbon they contain, along with some of the carbon in the underlying soil, is oxydized and released to the air, adding to the atmospheric pool of carbon dioxide (CO_2).

Though CO_2 makes up only a tiny share of the atmosphere, it serves a function vital to the earth's habitability. Like a one-way filter, it lets energy from the sun pass through it but absorbs the longer wavelength radiation emitted from the earth, a phenomenon dubbed the "greenhouse effect." In this way, CO_2 helps regulate the earth's temperature; without it, the earth would be covered with ice.

Over the last century, the clearing of forests and the burning of carbon-based fossil fuels—coal, oil, and natural gas—have raised the concentration of atmospheric CO_2 by a fourth. Just since 1958, when scientists began to monitor CO_2 levels routinely, it has risen 10 percent. A continuing rise in CO_2 levels, along with increases in the concentrations of other greenhouse gases, threatens to warm the earth, shifting rainfall patterns worldwide, disrupting crop production and water supplies, and threatening coastal areas with rising sea levels.

Earlier in this century, deforestation was the leading cause of the CO_2 buildup, but in recent decades it has been eclipsed by the booming use of fossil fuels. Today forest clearing releases between 400 million and 2.5 billion tons of carbon to the atmosphere annually, compared with more than five billion tons from the burning of coal, oil, and natural gas. Just five countries are believed to account for half of deforestation's contribution: Brazil, Indonesia, Colombia, Ivory Coast, and Thailand. Brazil alone may account for as much as a fifth.

Despite mounting evidence of deforestation's costly consequences, efforts to protect and more wisely manage the world's tropical forests remain woefully inadequate. One promising initiative was taken in late 1985, however, with the launch of the Tropical Forestry Action Plan. Jointly sponsored by FAO, the United Nations Development Program, the World Resources Institute, and the World Bank, the plan calls for accelerated forestry investments totaling $8 billion over five years.

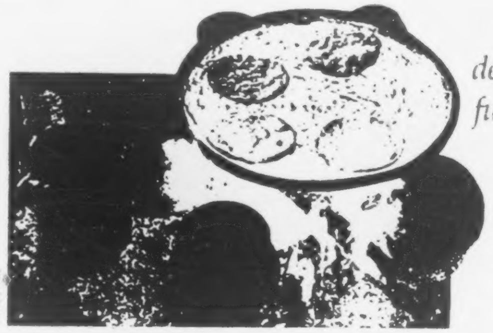
Already the Action Plan has stepped up funding commitments. Collectively, global aid contributions to forestry are likely to increase from roughly $600 million in 1984 to over $1 billion in 1988.

Another hopeful sign came in 1985 with ratification of the International Tropical Timber Agreement. Unique among commodity agreements, the ITTA calls for national policies that "encourage sustainable utilization and conservation of tropical forests and their genetic resources." The Tropical Timber Council established under the Agreement has so far approved a dozen projects amounting to roughly $2.8 million dealing with reforestation, sustainable forest management, and trends in timber markets.

No infusion of dollars, however large, can alter the present course of forest destruction without the institutions and social mechanisms to direct those dollars to the problem's core. With deforestation's causes deeply rooted in population growth, landlessness, Third World indebtedness, and exploitive policies, strategies to safeguard the forests will succeed only if they address these fundamental issues.

Hints of progress on these fronts engender some optimism. But the deforestation dilemma still cries for more vision and concerted action by governments and international organizations everywhere. It is neither plausible nor equitable to expect the developing countries endowed with tropical forests to shoulder the burden of their preservation unaided. These forests' intrinsic role in maintaining ecologic integrity, stabilizing climate, and protecting the earth's biological diversity make them global assets warranting a global commitment to their preservation. **AI**

"Fuelwood and other organic fuels are the sources of energy for survival of the world's poor. To live, man must eat. To be edible, most food must be cooked. . . . Close to half of mankind depends on fuelwood."



© Conrad

From a report of the United Nations Conference on New and Renewable Sources of Energy, Nairobi, August 1981

February 1988

Prepared for
United States Department of Energy

Office of Energy Research
Office of Basic Energy Sciences
Carbon Dioxide Research Division
Washington, D.C. 20585

DOE/NBB-0082
Dist. Category UC-11

TRO39

The Prospect of Solving the CO_2 Problem through Global Reforestation

Prepared by: Gregg Marland
Oak Ridge Associated Universities
Institute for Energy Analysis
P.O. Box 117
Oak Ridge, TN 37831-0177

and

Environmental Sciences Division
Oak Ridge National Labortory
P.O. Box X
Oak Ridge, TN 37831-6038

Under Contract No. DE-AC05-76OR00033
DE-AC05-OR21400

DISCLAIMER

"This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A05
Microfiche A01

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts, (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from (NTIS) at the above address.

CONTENTS

Page

List of Figures v

List of Tables vii

Abstract ix

Introduction 1

Land Area and Forest Area 4

Current Trends in Forest Area 8

Cumulative Changes in Forest Area 19

The Situation in the United States 25

Forest Growth Rates 31

Further Thoughts 48

The Prospects for Large Scale Plantations 51

Conclusion 55

Acknowledgements 59

References 60

LIST OF FIGURES

Figure Page

1 Changing land use and population since 1880 in Pakistan, Bangladesh, Burma, Malaysia, Brunei, and Northern India. Data from Richards et al., 1987 18

2 Worldwide area in agriculture (----) and rate of clearing (——). From Houghton et al. 1983 21

3 Net flux of carbon to the atmosphere as a result of land-use changes and harvests in Latin America, Tropical Africa, North America, and Europe. From Houghton et al., 1983 22

4 (above) Land in all forests, commercial forests, and cropland in farms in the United States, 1800 to 1975. (below) Standing volume of sawtimber at different dates in the United Sates, 1800 to 1977. From Clawson, 1979 30

5 Relationships of biomass, net annual production, and leaf area index to stand age. From Marks and Bormann, 1972 33

6 Relationship between biomass of forest components and stand age in a Tropical Moist Forest Life Zone. From Brown, 1980 34

7 Relationship between above-ground biomass in temperate (left) and tropical (right) forests and stand age. From Brown and Lugo, 1982 37

8 Influence of site quality, measured as site index (S.I.), and age on merchantable volume increment in *P. elliottii*. 45

LIST OF TABLES

Table		Page
1	The Largest Fifteen Countries on Earth Ranked By Total Land Area, Area of Closed Forest, Population, and Emissions of CO_2 From Fossil Fuel Burning	6
2	An 11-Country Sample to Focus the CO_2 Problem	7
3	Forested Land in The U.S.S.R.	10
4	Areas of Natural Woody Vegetation in the Tropics, Estimate for Year End 1980	13
5	Annual Rates of Deforestation and Plantation in the Tropics (1981-1985)	14
6	Populations Involved in Fuelwood Deficit Situations . . .	15
7	Forest Clearing in Africa	17
8	Population Projections for Latin America	20
9	Comparison of Areal Estimates of Major Ecosystems Derived From the Newly Compiled Vegetation and Land-Cover Data Bases	24
10	Data on Commercial Forest Land in the United States, 1977 (Data from U.S. Forest Service, 1982)	26
11	Net Growth per Hectare of Growing Stock, All Species, Commercial Forests, by Major Ownership Class, and by Region, 1977	29
12	Mean Net Annual Growth For Current Commercial Forest Areas	39
13	Growth Rates of Stemwood in Some Managed Forests and Plantations	41
14	Productivity Increases Attributable to Intensive Plantation Management	42
15	Nutrient Distribution Within Major Parts of the Tree as a Percent of Total Content, Total Nutrient Content and Biomass of Five Species	46
16	Increase in Forest Area and/or Productivity Required in Order to Remove an Additional 5 x 10^9 Tons of Carbon Per Year From the Atmosphere	57

ABSTRACT

We are confronted with the possibility that it may become necessary to try to limit the increase in atmospheric CO_2 in order to avert adverse changes in the global climate. One short-term approach would be to stimulate the growth of forests to take up in woody matter enough carbon to balance the discharge of CO_2 from fossil fuel burning. This study evaluated the extent to which the area and/or net growth rate (mean annual increment) of global forests would need to be enhanced in order to remove an additional 5×10^9 tons of carbon per year from the atmosphere.

Although it is physically possible to plant large areas of new plantation and/or to stimulate tree growth via advanced silviculture techniques, conflicts in land use and resource allocation are quickly encountered in efforts of sufficient magnitude. The scale of the effort required is approximately equal to doubling the net annual yield of all of the world's closed forests or planting new fast growing forests over an area equivalent to the total of global forest clearing to date. The cost of such a scheme is immense but it needs to be compared with the costs of other approaches to dealing with atmospheric CO_2 or of coping with the attendant changes in climate.

It is clear that although it is impractical to think in terms of solving the CO_2 problem through forestry alone, forestry could play a significant role.

INTRODUCTION

Carbon dioxide is an essential component of the earth's atmosphere, providing a source of carbon for photosynthesizing green plants. Because of its optical properties, atmospheric carbon dioxide also plays an important role in the global heat balance. It is generally accepted that the equilibrium temperature at the earth's surface is a function of the concentration of carbon dioxide in the atmosphere and that if the CO_2 concentration were to rise, the mean earth surface temperature would likewise rise. The magnitude and consequences of this temperature rise have been the object of intense study for several decades but remain subject to considerable uncertainty.

What is certain is that the concentration of carbon dioxide in the atmosphere is rising. Although the natural geochemical cycling of carbon through the atmosphere-biosphere-ocean system involves very large quantities of carbon, over the last several centuries the activities of man have caused excess quantities of carbon dioxide to be released to the atmosphere. Carbon dioxide has been released in large and increasing quantities as a consequence of burning fossil fuels and through a continuing decrease in the total mass of the terrestrial biosphere, i.e., through the destruction of forests.

We are now confronted with the possibility that it may be necessary to try to limit the increase in atmospheric CO_2 in order to avert adverse changes in the global climate. Ultimately the only way to prevent the CO_2 level from rising is to stop oxidizing fossil fuels and to halt further erosion in the mass of carbon stored in vegetation and soils. On a globe confronted with trying to feed an ever-expanding population and with an energy system and economy largely dependent on consuming fossil fuels, this presents a formidable target. For the nearer term, then, we must inquire if there is some way to prevent further CO_2 buildup without shutting down the global economic system.

Is there some transient means that would halt or reverse the CO_2 increase for perhaps decades while the world developed and put in place an energy system that did not rely on fossil fuels? There has been some considerable speculation on this topic (Albanese and Steinberg, 1980; Baes et al., 1980; Dyson and Marland, 1979; Marchetti, 1976). What is required is some way to collect carbon and some place to put it so that it does not accumulate in the atmosphere as carbon dioxide. Most such speculation has focused on mechanical/chemical systems for collecting CO_2 as a gas or liquid and then trying to dispose of it either in deep oceans or deep rock formations. Collecting CO_2 at concentrated sources is readily accomplished although very expensive. Disposing of CO_2 in large quantities is highly speculative and ecologically worrisome. The prospects along this line have been succinctly summarized by Marland (1987). None of these proposals offered to date are sufficiently attractive to seriously contemplate implementation.

A viable option that remains is to take advantage of photosynthetic plants and to collect and store carbon as plant tissue. This is an option that was first elaborated by Dyson (1976) and Dyson and Marland (1979) but has not been adequately explored. The intent of this paper is to revisit this idea and those admittedly naive first thoughts and to provide more insight into the feasibility of such a scheme. Because forests comprise 90 percent of the carbon in terrestrial vegetation (Armentano and Ralston, 1980), and because woody trees contain vastly higher ratios of carbon to other nutrient elements (that we might have to provide as fertilizer) than do other plant tissues, attention here will focus on storing carbon in trees. Houghton et al. (1983) concluded that the most important changes in the mass of carbon held on land are changes in forest mass (i.e., harvest, clearing for agriculture, reforestation) and we can think simultaneously of changes in forests and carbon release or recovery from the atmosphere. About one-third of the net carbon flux from cleared forest land is from the disturbed forest soils.

Dyson and Marland (1979) contemplated the circumstance that annual CO_2 emissions reached twice the 1976 value before a perception of acute ecological disaster and a consensus for action could be achieved. They also presumed, without elaboration, that since only half of the apparent excess CO_2 emissions now accumulates in the atmosphere (the remainder being sequestered somewhere else in the carbon cycle, presumably the ocean), a CO_2 collection system would be adequate if it collected half of the then-current annual emissions. The question they then posed was: What would it require to remove 5×10^9 tons of carbon, as carbon dioxide, from the atmosphere annually for a period long enough to allow society to overcome its addiction to fossil fuels? Net global photosynthesis (net primary productivity) has been estimated at 50 to 60×10^9 tons C yr^{-1} (SCEP, 1970; Gates, 1985; Houghton et al., 1985a), so we are contemplating promoting a 10 percent increase in carbon assimilation in such a way that the additional carbon will be in long-lived tree parts. Dyson and Marland envisioned that trees growing at the rate of cultivated American sycamore in the southeastern U.S. could take up carbon at the rate of 7.5 tons C ha^{-1} yr^{-1} (based on data from Steinbeck and Brown, 1976). If the trees were left unharvested to store carbon, about 700×10^6 ha of land would be required to sequester the necessary carbon at this rate. For periods longer than the maximum life cycle of these trees, some method would have to be devised to harvest one crop of trees and prevent its oxidation while a second crop was continued. Dyson and Marland cited Fraser et al. (1976) to the effect that the United States contains 70×10^6 ha of currently unproductive land with suitable rainfall for this purpose (greater than 50 cm yr^{-1}).

The reality of course, is that in many areas of the world, forest is still being cleared and we must think in terms of net forestation, of first halting the loss of existing forests and then increasing either the area or carbon density of forests. We also know that much of global forest is boreal or tropical and can be expected to grow respectively slower or faster than American sycamore in Georgia.

Intense silviculture (fertilization, irrigation, weed control, thinning, fire and pest control, etc.) can have profound impact on growth rates, and genetic engineering may be helpful.

This study is thus a second level of discussion. I have given some consideration to variations in growth rate and some consideration to where plantations might be possible. I have considered increasing the productivity rather than the area of forests. The possibilities of genetic engineering and intense silviculture are described briefly. If is useful to retain 5 x 10^9 tons C yr^{-1} as an index for thinking about the magnitude of the effort being contemplated.

LAND AREA AND FOREST AREA

It is instructive to begin by examining the total land area and total existing forest area of the earth. In doing so it needs to be understood that the data on forest area have a very high uncertainty and for some countries significantly different values can be found in various reference sources. Molofsky et al. (1986) tried to address the difference between two widely cited recent inventories of tropical forest (Myers, 1980; and FAO, 1981) and concluded that while there are no systematic discrepancies, there are major differences. For four countries the difference between the two sets of values exceeds 50 percent. Clearly a significant portion of the difference is the result of definitional problems with various country and regional data sets. The differences are even greater when one attempts to compare deforestation rates.

It is beyond the scope of this paper to try to resolve questions regarding the quality of, or differences among, various data sets. In any event, our interest is still at the level of gross trends and orders of magnitude. For the moment we accept data from a variety of sources that have attempted to provide reasoned insight and trust that the data are not qualitatively misleading. We believe that there are enough data in qualitative accord to support the conclusions drawn here.

The earth contains an estimated 4,000 x 10^6 hectares of forest of which 2,050 x 10^6 are classified as temperate or boreal, 1,750 x 10^6 as tropical and 300 x 10^6 as arid (FAO, 1985a). Closed forest has the highest carbon density and comprises 1,650 x 10^6 ha of the temperate forest and 1,200 x 10^6 ha of the tropical forest. Closed forests, according to UN FAO definition, are forests in which "by their different strata and their undergrowth cover a large part of, or all, the ground and which, in general, do not have a continuous herbaceous stratum." (FAO, 1982) and are not used for purposes other than forestry. In Table 1 I show the largest 15 countries on earth by land area and by area of closed forest. The largest 15 countries contain 66 percent of the global land surface so should give a good sampling of where the prospects for reforestation must be. The list includes four countries from the North Africa/Mid East area with virtually no prospect of forests. The top 15 countries by area of forest contain 80 percent of closed forests. After the big five--U.S.S.R., Brazil, Canada, U.S.A., And China--forests are found largely in a variety of underdeveloped, tropical countries. Over 50 percent of tropical, closed forest is contained in only three countries--Brazil, Zaire, and Indonesia. There are only 136 x 10^6 ha of closed forest in all of Europe (excluding the U.S.S.R.) (FAO, 1976).

Table 1 also lists, for contrast, the largest 15 countries by population and by 1982 emission of CO_2 from fossil fuel burning. In these last two lists we begin to encounter the countries of Japan and Europe so obvious in their absence from the first two lists.

Five countries (U.S.S.R., U.S.A., China, India, and Mexico) appear on all four lists. By adding Brazil, Canada, Indonesia, and Japan, we embrace 50 percent of the global total for all four categories, almost 70 percent of closed forests (see Table 2). Adding Zaire and West Germany brings the sums for CO_2 emissions and forest area past two-thirds of the global total and provides a striking contrast. Of Western European countries, West Germany is the most populous and emits the most CO_2. Zaire is one of the largest countries in Africa and

TABLE 1. THE LARGEST FIFTEEN COUNTRIES ON EARTH RANKED BY TOTAL LAND AREA, AREA OF CLOSED FOREST, POPULATION, AND EMISSIONS OF CO_2 FROM FOSSIL FUEL BURNING.

	By Total Area		By Area of Closed Forest		By Population (1985)		By CO_2 Emissions (1982)	
	Total Land Area (10^6 ha)	13,078	Total Closed Forest (10^6 ha)	2,937	Total (10^6)	4,842	Total (10^6 tons C)	4,749
1.	U.S.S.R	2227	U.S.S.R	792	China	1063	U.S.A.	1135
2.	China	933	Brazil	396	India	761	U.S.S.R	901
3.	Canada	922	Canada	264	U.S.S.R	278	China	413
4.	U.S.A	913	U.S.A.	195	U.S.A	237	Japan	227
5	Brazil	846	China	125	Indonesia	165	W. Germany	181
6.	Australia	762	Indonesia	123	Brazil	135	U.K.	141
7.	India	297	Zaire	106	Japan	120	Poland	112
8.	Argentina	274	India	73	Pakistan	102	France	111
9.	Algeria	238	Peru	71	Bangladesh	101	Canada	108
10.	Sudan	238	Mexico	48	Nigeria	95	India	105
11.	Zaire	227	Colombia	47	Mexico	79	Italy	88
12.	Saudi Arabia	215	Bolivia	44	W. Germany	61	E. Germany	83
13.	Mexico	192	Australia	42	Viet Nam	59	Mexico	74
14.	Indonesia	181	Papau/New Guinea	34	Italy	57	S. Africa	67
15.	Libya	176	Venezuela	33	U.K.	56	Czechoslovakia	64
	Sum	8640		2393		3369		3810
	% of Total	66.07		81.48		69.58		80.23

Area and population data from World Resources Institute, 1986.

TABLE 2. AN 11-COUNTRY SAMPLE TO FOCUS THE CO_2 PROBLEM

		Land Area (10^6 ha)	Closed Forest (10^6 ha)	1985 Population (10^6)	1982 CO_2 Emissions (10^6 tons C)	fossil fuel CO_2 emissions / area of closed forest (tons Cyr^{-1}/ha forest)
1.	U.S.S.R	2227	792	278	901	1.1
2.	U.S.A	913	195	237	1135	5.8
3.	China	933	125	1063	413	3.3
4.	India	297	73	761	105	1.4
5.	Mexico	192	48	79	74	1.5
	Sum (1-5)	4562	1233	2418	2628	
	% of Total	34.89	41.98	49.94	55.34	
6.	Brazil	846	396	135	42	0.1
7.	Canada	922	264	26	108	0.4
8.	Indonesia	181	123	165	21	0.2
9.	Japan	37	24	120	227	9.5
	Sum (1-9)	6548	2040	2864	3026	
	% of Total	50.07	69.46	59.15	63.72	
10.	Zaire	227	106	33	1	0.01
11.	W. Germany	24	7	61	181	25.9
	Sum (1-11)	6800	2153	2958	3208	1.5
	% of Total	52.0	73.3	61.1	67.6	

Area and population data from World Resources Institute, 1986.

contains the most closed forest of any African nation. It seems fair to say that we can characterize the global situation rather well by looking at these eleven countries. If the biosphere is the solution, then these 11 nations comprise the bulk of the problem and must comprise the bulk of the solution.

With the focus currently on the rapid rate of clearing of tropical forests--a problem with many ramifications beyond the CO_2 issue (Myers, 1976)--displaying the ratio between CO_2 emissions from fossil fuel burning and forest area (Table 2) gives us some indication of the political self-interest of those countries with large areas of tropical forest (Brazil, Indonesia, Zaire).

CURRENT TRENDS IN FOREST AREA

The initial challenge for reforestation lies in the fact that in net we are still deforesting the earth. While some areas in the temperate Northern Hemisphere are experiencing a net increase in the area of forests, due largely to abandonment of marginal agricultural land, the earth as a whole is still experiencing a net deforestation. A terrestrial vegetation that contained 900×10^{15} g C (Olson et al., 1985) before the inception of agriculture (756×10^{15} g in the woody parts of trees) is now down to some 560×10^{15} g C (Olson and Watts, 1982) and continues to decrease.

According to a U.S. Interagency Task Force (1980), the tropics, which comprise over 30 percent of the earth's land surface (4.6×10^9 ha), are 42 percent forest by area ($1900 \times 10^6 = 1100 \times 10^6$ ha of closed forest plus 800×10^6 ha of open forest). These closed forests are being cleared at a rate of at least 7.3×10^6 ha yr^{-1} and perhaps as much as 20×10^6 ha yr^{-1}. The most cited values for clearing of closed tropical forest are on the order of 12×10^6 ha yr^{-1} (see also Houghton et al., 1985a). With 2.4 percent per annum growth, the population of tropical countries would increase from 2 billion in 1980 to over 3 billion in 2000, accompanied by an increase of 100×10^6 ha of land under permanent cultivation (USITF, 1980). Huge increases in forest production will be necessary just to keep pace with the demand for fuelwood. The World Bank estimates that 20-25 x 10^6 ha of new tree plantations will have to be established by the year 2000 to meet future firewood needs (Nambiar, 1984).

On the other hand, a U.S. Department of Energy workshop (Armentano and Hett, 1980) estimated that commercial timberlands in the north temperate zone are functioning as a net sink for 10^9 tons of carbon per year. There was a total net increase in forest area in the European Economic Community countries by 1.6 x 10^6 ha between 1950 and 1977. The FAO (1976) sees increases in closed forest area in every subregion within Europe continuing over the next quarter century. The major recent increase in temperate closed forest is due to conversion of previously poorly stocked forest land.

Forest area in New England was 40 percent greater in 1970 than in 1890, but still well short of the 1600 A.D. value (Armentano and Hett, 1980). Delcourt and Harris (1980) showed that somewhere between 1950 and 1960 the southeastern United States experienced a turn-around and is now being reforested in net. The southeast U.S. was 91.6 percent forest before settlement and, although little virgin forest remains, over the last few decades there has been an increase in holdings of intensively managed forest land, on which net annual growth has increased due to reforestation of nonstocked areas and control of species composition and stand density. While only 1 percent of virgin forest remains, Armentano and Hett (1980) estimate 51 percent of the original forest land is still forested, even if at lower biomass density.

Holowacz (1985) reports that in the U.S.S.R. both area of forested land and volume of growing stock have increased regularly since at least 1961 (see Table 3).

Armentano and Ralston (1980) found net forest growth throughout the north temperate zone, particularly in North America and in Siberia, but also in Western Europe and temperate Asia. Temperate zone forests

TABLE 3. FORESTED LAND IN THE U.S.S.R.

	Area of Forested Land (10^6 ha)	Volume of Growing Stock (10^6 m^3)
1961	738	80,200
1973	769	81,900
1978	792	84,200
1984	811	85,900

From Holowacz, 1985.

comprise 34-40 percent of the world's biotic carbon and are acting as a sink for 1.0 - 1.2 x 10^9 tons C yr^{-1} (Armentano and Ralston, 1980).

Although data from China are not good, Smil (1983) worries that 20 x 10^6 hectares have been deforested there in the last three decades and that reforestation has been less successful than is generally portrayed.

Detwiler et al. (1985) present figures to suggest 1.2-1.5 x 10^9 tons of C were released to the atmosphere in 1980 from destruction of tropical vegetation (including 0.3 x 10^9 tons from disturbed soils). Houghton et al. (1987) calculated 1.0 to 2.6 x 10^9 tons carbon per year as the annual net flux from the global biosphere (0.1 from temperate and boreal zones) in 1980 from changes in land use (about one-third from disturbed soils). Other estimates abound (see Table 6.3 in Houghton et al., 1985a) but the consensus is clearly that temperate areas that were cleared decades to centuries ago are experiencing modest gains in forest area while major deforestation continues in the tropics. The overall range for recent studies suggests 0.6 - 2.6 x 10^9 tons C yr^{-1} as the net annual flux from terrestrial ecosystems to the atmosphere as a result of land use changes (Houghton et al., 1985a); almost entirely from the tropics. Unlike temperate areas where minor increases in growing stock, if not forest area, are now occurring; in the tropics deforestation continues in the face of settlement pressure and economic demands for pasture, agricultural land, and/or wood products. (Houghton et al., 1985b, point out that uncertainty in the rate of release of carbon is about equally distributed among rate of deforestation, the stature of the forests cleared, and the length of time the forests remain cleared.)

We focus briefly on the tropics to gain a sense of the pressure on existing forests. Lanly (1982) provides an estimate of the inventory and current destruction rates of forests in 76 tropical countries. Note that Lanly's estimates are based on country by country surveys and questionnaires by the United Nations Food and Agriculture Organization (FAO), but are among the lowest published estimates of forest destruction. As seen in Table 4, the tropics currently contain 1200×10^6 ha of closed forest, 734×10^6 ha of open forest and another 1033×10^6 ha of forest fallow and shrub formations. The tropics are also experiencing population growth at 2.63 percent per year, and according to Lanly (1982) are being deforested at a rate of 11.3×10^6 ha per year (7.5 million hectares of closed forest and 3.8×10^6 ha of open forest) (see Table 5).

With this trend, large and growing populations are experiencing deficits of fuelwood, especially since forest clearing is concentrated among the most accessible forests (Table 6). "Extrapolation of present trends in population, deforestation and plantation work produces a picture of a gigantic problem by the year 2000.... The deficit might reach nearly one thousand million m^3 of fuelwood" (de Montalembert and Clement, 1983, p. 23). On this count, Lanly (1982) does urge us to be cautious of "globalization." Many problems are not exportable and over-exploitation of firewood is characteristic not of tropical moist forests but of dry tropical regions where open tree formations predominate. On the other hand, in practically every country the periphery around large urban areas and along main roads are over exploited for fuelwood (Lanly, 1982). There is additional degradation of open tree formations by over-grazing and by repeated burning. Also, even where fuelwood harvests do not result in forest destruction, they may degrade existing forests by reducing stocking density and stand volume. Fearnside (1986) also cautions that clearings in Amazonia are concentrated in a few parts and aggregated regional data can hide some of the great impacts. In Amazonia the opening of access routes is being followed by extensive immigration and clearing.

According to Myers (1980), 20.0×10^6 ha per year of tropical forest are being converted from a primary state to a human-impacted state, half of this being permanently deforested.

"The main cause for the continued destruction of the world's tropical forests. . .is the increasing demand for agricultural land to supply the needs of rapidly growing populations" (FAO, 1982, p.iii).

TABLE 4. AREAS OF NATURAL WOODY VEGETATION IN THE TROPICS, ESTIMATE FOR YEAR END 1980 (10^6 ha)

Region	Tree Formation				Fallows of:					
	Closed	Open	Total	% of land	closed tree formations	open tree formations	shrub formation	Grand Total	Population (10^6)	Rate of Population Growth (1975-1980) (%)
Tropical America (23 countries)	679	217	896	53.32	109	62	146	1,212	322	2.89
Tropical Africa (37 countries)	217	486	703	32.11	62	104	443	1,312	344	2.95
Tropical Asia (16 countries)	306	31	336	35.61	69	4	36	445	1,263	2.43
Total (76 countries)	1,201	734	1,935	40.20	240	170	624	2,969	1,929	2.63

Data from Lanly, 1982.

TABLE 5. ANNUAL RATES OF DEFORESTATION AND PLANTATION IN THE TROPICS (1981-1985) (10^3 ha)

Region	Annual Rates of Deforestation Tree Formations			Annual Rates of Plantation	Plantation: Deforestation Ratio	Areas of Established Plantation at end of 1980
	Closed	Open	All			
Tropical America (23 countries)	4339	1272	5611	535	1 : 10.5	4620
Tropical Africa (37 countries)	1331	2345	3676	126	1 : 29	1780
Tropical Asia (16 countries)	1826	190	2016	438	1 : 4.5	5111
Total (76 countries)	7496	3807	11303	1099	1 : 10	11511

From Lanly, 1982.

TABLE 6. POPULATIONS INVOLVED IN FUELWOOD DEFICIT SITUATIONS[1]
(10^6 inhabitants)

	1980						2000	
	Acute Scarcity[2]		Deficit[2]		Prospective Deficit		Acute Scarcity or Deficit[2]	
Region	Total Population	Rural Population	Total Popuaction	Rural Population	Total Population	Rural Population	Total Population	Rural Population
Africa	55	49	146	131	112	102	535	464
Asia and Pacific	31	29	832	710	161	148	1671	1434
Latin America	26	18	201	143	50	30	512	342
Total	112	96	1179	984	323	280	2718	2240

---

[1] Total population and population with a predominantly rural type of energy consumption (total population less urban centers over 100,000 inhabitants) in the areas under the identified fuelwood situations.

[2] Definition of categories:

- acute scarcity: zones or countries in negative wood energy balance where existing fuelwood resources have been depleted to the point where populations cannot obtain sufficient fuelwood even through overcutting; consumption is below minimum needs;
- deficit: zones or countries where populations are still able to meet their minimum fuelwood needs, but only by overcutting existing resources. These are already insufficient to meet present needs on a sustainable basis and are being depleted.

From Lanly, 1982.

By the year 2000, an additional (with respect to 1982) 150 million hectares of closed forest and 76 million hectares of open tree formations are expected to be cleared (Lanly, 1982).

For the specific tropical countries the situation varies significantly, even among the three countries containing the most forest. In Brazil the main cause of deforestation is small-holder farming and cattle raising related to resettlement patterns and opening up new areas (Molofsky et al., 1986). Deforestation is at rates of 1.0-1.5 x 10^6 ha yr^{-1}--perhaps as high as 2.3 x 10^6 ha yr^{-1}--and, according to government estimates, another 80 x 10^6 ha can be expected to be cleared for agricultural and other uses (Molofsky et al., 1986). In Indonesia and Zaire the principal cause of forest destruction is shifting cultivation. The increasing number of people involved in shifting cultivation seems to be both increasing the amount of land involved and shortening the fallow cycle. The current rate of deforestation in Zaire is still a relatively small 0.18 x 10^6 ha yr^{-1}, whereas the FAO estimate for Indonesia is 0.6 x 10^6 ha yr^{-1}, (Molofsky et al., 1986). The principal locus of deforestation in Africa now is Nigeria and the Ivory Coast in central west Africa (Lanly, 1982) (see Table 7). Lanly (1982) suggests that throughout the tropics shifting cultivation is responsible for 35 percent of forest clearing. Extensive grazing is the next most important cause, followed by permanent agriculture, hydroelectric development, development of infrastructure, and urbanization. In Africa, 70 percent of clearing of closed forests is for shifting agriculture and, according to Brown and Wolfe (1985), the only way some African farmers can increase harvests to feed the growing population is by clearing new fields. Jordan et al. (1986), suggest some clearing in the Amazonian basin may be solely for the purpose of establishing proprietary rights.

Data from south and southeast Asia (Richards et al., 1987) provide us with a 100-year record of the loss of forest area as population and arable land area increased (Figure 1).

TABLE 7. FOREST CLEARING IN AFRICA

Region	Amount of Closed Forest (10^3 ha)	Annual Clearing (10^3 ha)	% Cleared Annually
Central West Africa	13,752	703	5.1
Zaire Basin	171,540	351	0.2
East Africa	12,957	105	0.8
	198,249	1,159	0.6

From Brown and Wolfe, 1985.

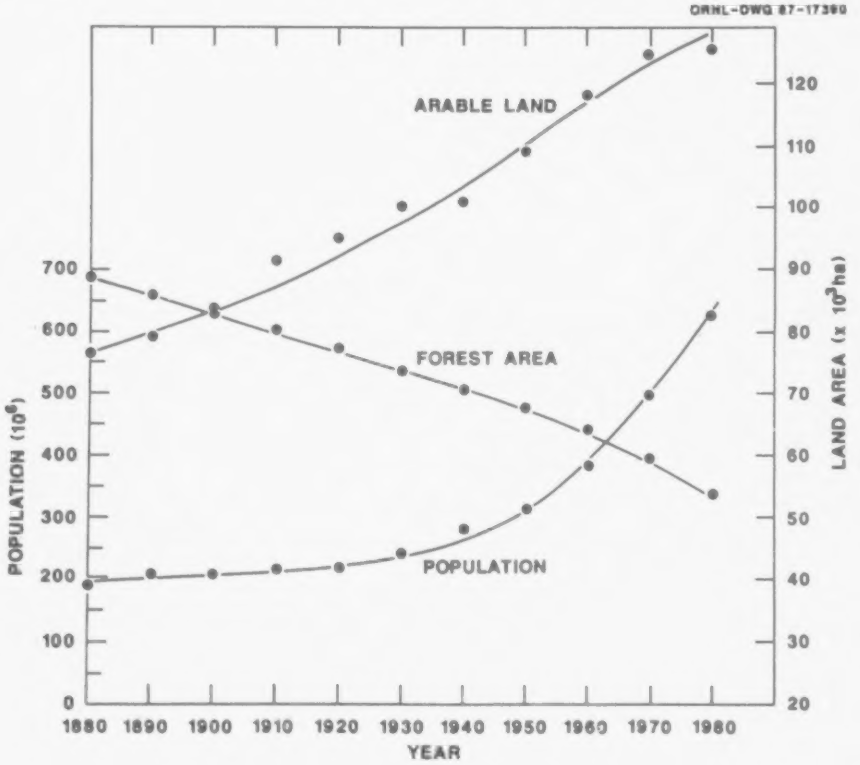


Figure 1. Changing land use and population since 1880 in Pakistan, Bangladesh, Burma, Malaysia, Brunei, and Northern India. Data from Richards et al., 1987.

Population projections capture the essence of the clearing problem in, for example, Latin America. Merrick (1986) shows that whereas the areas and populations of North and Latin America were approximately equal in 1950, by 1985 Latin America contained 50 percent more people and by 2025 it may be more than twice as populous (Table 8).

The rate of development of tree plantations in the tropics is barely one-tenth the rate of forest clearing and the total area of plantation is slightly over a year's clearing (Table 5). The current contribution of plantations is small but according to Lanly (1982, p. 101), "everything points to the fact that the amount of plantation will continue to increase."

CUMULATIVE CHANGES IN FOREST AREA

Returning to a global basis, Matthews (1983) estimates there are 1,500 x 10^6 ha of land in global agriculture (compared to 1,450 x 10^6 ha in the FAO [1980] estimate) with another 260 x 10^6 ha in unreported subsistence agriculture. This represents land that has been removed from some natural ecosystem type. The greatest reduction from pre-agricultural extent for natural ecosystems is 650 x 10^6 ha of nontropical forests with another 50 x 10^6 ha of tropical forests, 650 x 10^6 ha of grassland, and 210 x 10^6 ha of woodland. (Houghton [1986] cautions that cultivated land is not a good measure of forest clearing as clearing for pasture has accounted for about 35 percent of the carbon flux since 1860 and much additional clearing of forest has been for other than cropland.)

Houghton et al. (1983) (based on FAO data) agree that about 1500 x 10^6 ha of land are involved in agriculture (see Figure 2) and have shown dramatically how the history of the associated land use changes, i.e., forest clearing and CO_2 flux to the atmosphere, has differed between the northern temperate zone and the tropical forest areas (Figure 3). The total area of cultivated land has increased by 850 x 10^6 ha just since 1860 (Houghton et al., 1985a). Over the last 100-200 years the total net release of carbon from terrestrial

TABLE 8. POPULATION PROJECTIONS FOR LATIN AMERICA

		Population (10^6)		Land Area (10^6 ha)
	1950	1985	2025	
North America	166	264	345	1950
Latin America	165	405	779	2050
Brazil	53	136	246	
Peru	8	20	41	
Venezuela	5	17	38	
Colombia	12	29	52	

Data from Merrick, 1986.

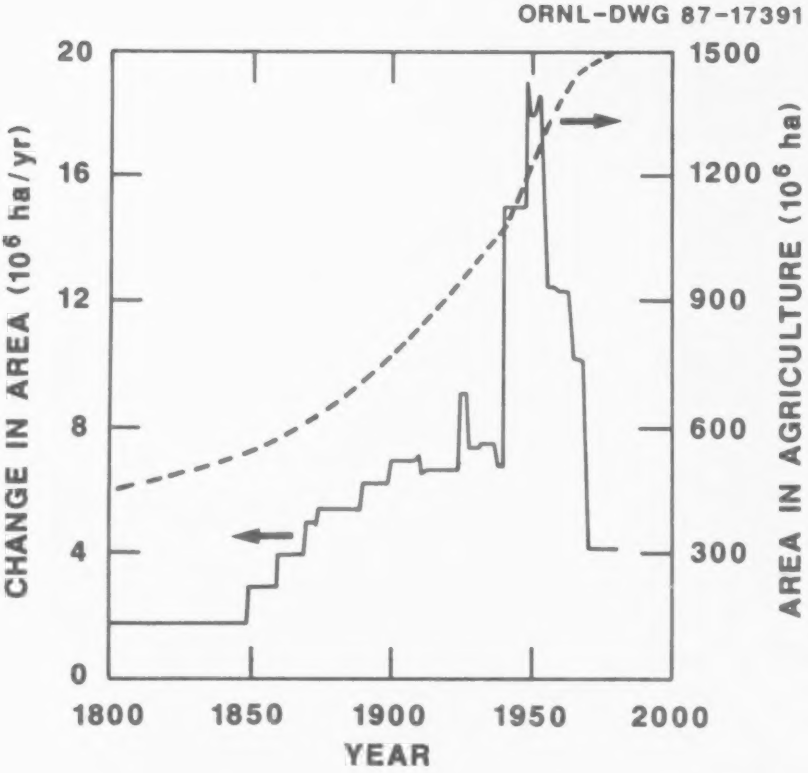


Figure 2. Worldwide area in agriculture (----) and rate of clearing (——). From Houghton et al. 1983.

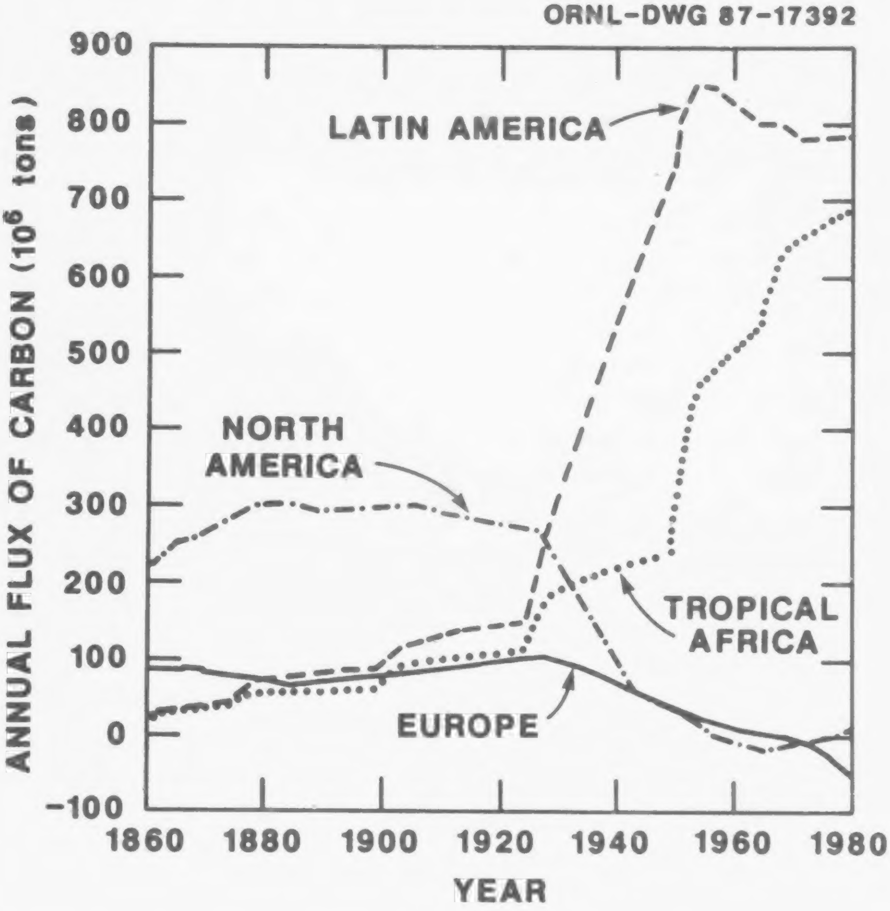


Figure 3. Net flux of carbon to the atmosphere as a result of land-use changes and harvests in Latin America, Tropical Africa, North America, and Europe. From Houghton et al., 1983.

ecosystems, has been 90-180 x 10^9 tons C (Houghton et al., 1985a.) Based on measurements of air bubbles in old polar ice, Siegenthaler and Oeschger (1987) have estimated that the total carbon release from the biosphere prior to 1980 was 90-150 x 10^9 tons.

Aside from providing perspective on the regional differences in the timing of forest clearing and on the current interest in tropical forests, these data provide some bounds on our vision for reforestation. As a first cut one might envision that the long-time biological succession patterns, i.e., pre-agricultural distribution of biomes, would provide some realistic limits on where forests might be established. Although the possibility of irrigation and/or fertilization widen the prospects some, and changes in climate might have some impact, the original extent of forests gives us a preliminary upper bound for the ultimate reintroduction of forests. Houghton et al. (1983) envision a 1700 A.D. world with 1352 x 10^6 ha of tropical moist forest, 828 x 10^6 ha of tropical seasonal forest, 1158 x 10^6 ha of temperate forest, and 1179 x 10^6 ha of boreal forest. Although much clearing took place in Europe and Asia prior to 1700, these numbers are of the same order of magnitude as Matthews' (1983) estimates of 1277 x 10^6 ha of rain forest and 3351 x 10^6 ha of other forest prior to agriculture conversion. Summing the two categories of tropical forest likewise yields a sum (2180 x 10^6 ha) not out of line with Lanly's (1982) estimate that there are 1934 x 10^6 ha of tropical forest now. The Matthews data (Table 9) thus give us some idea, on a global basis, of the total land area which once accommodated forest but no longer does so. Obviously much of this has been preempted by agricultural or other uses. Accepting the data of Matthews and of Lanly, total global deforestation has amounted to 700 x 10^6 ha and continues at a rate of 11.3 x 10^6 ha yr^{-1} in the tropics with a much smaller amount of reforestation of temperate areas. The prevailing trend is captured in data that show 29 percent of the land in maturely-developed Europe is in cultivation whereas only 12 percent of the land in North America and 9 percent of the land in South America are so committed (Merrick, 1986).

TABLE 9. COMPARISON OF AREAL ESTIMATES OF MAJOR ECOSYSTEMS DERIVED FROM THE NEWLY COMPILED VEGETATION AND LAND-COVER DATA BASES†

	Pre-agricultural Vegetation Area (10^6 ha)	Present Land Cover Area (10^6 ha)	Ecosystem Reduction	
			Area (10^6 ha)	Percent Total Ecosystem
Total forest	4628	3927	701	15.15
Tropical rain forest	1277	1229	048	3.75
Other forest	3351	2698	653	19.5
Woodland	1523	1310	213	13.8
Shrubland	1299	1212	087	6.7
Grassland	3390	2743	647	19.1
Tundra	734	734	000	0.0
Desert	1582	1557	025	1.6
Cultivation	093*	1756	-1663	---

*Limited areas with long use histories and for which reliable vegetation data could not be acquired have unavoidably been designated as cultivated in the vegetation data base.

†Ecosystem reduction figures indicate the extent to which ecosystems have been modified, through agricultural activities, relative to each other, and relative to their respective original extents. Ice-covered land is not included. Total area is 13,240 x 10^6 ha.

From Matthews, 1983.

The prospects for the future are, of course, somewhat clouded. While the FAO (1985a, page 16) reports "it has to be expected that some forest land will continue to be transferred to agricultural use, to meet the needs for increased agricultural production," others envision that world cropland area may not expand at all during the remainder of this century. Barr (1981) suggests that virtually all of the readily available, relatively fertile cropland in the developed and centrally-planned countries is already in use.

Interestingly, Matthews' (1983) estimate of the total area of global forest clearing to date is virtually identical to the Dyson and Marland (1979) estimate of reforestation that would be necessary to take up enough CO_2 to equal the current fuel releases.

THE SITUATION IN THE UNITED STATES

Although the United States is certainly not representative of countries as a whole, we can get some perspective of the variety of situations to be encountered by looking at some of the readily available U.S. Data (U.S. Forest Service, 1982). These data emphasize that assembling a simple inventory of world forest areas fails to provide much insight that we prefer to have. In the U.S. the nature, quantity, productivity and ownership patterns of forests differ regionally (Table 10).

Table 10 does not show the size of individual holdings but this is important when trying to influence forest management. A great deal of forest shown under "other private" ownership in Table 10 is in small parcels, is held for short term, or is held by owners with various objectives other than timber production. In Europe, 40 percent of privately-owned forests are in holdings of less than 10 ha (FAO, 1976). The 195.3 x 10^6 ha of U.S. commercial forest are, by definition, forests with productivity greater than 1.4 m^3 ha^{-1} yr^{-1} and not set aside as parkland or other protected areas (an additional 10.2 x 10^6 ha). The U.S. Forest Service (1982) tabulates another 92.6 x 10^6 ha of noncommercial forest. This is forest with

TABLE 10. DATA ON COMMERCIAL FOREST LAND IN THE UNITED STATES, 1977
(Data from U.S. Forest Service, 1982)

		U.S. Total	North	South	Rocky Mountain	Pacific Coast
Area	Total Land Area (10^6 ha)	912.9	252.5	205.3	224.2	230.9
	Total Forest Area (10^6 ha)	298.2	71.9	83.8	55.7	86.8
	Commercial Forest Area (10^6 ha)	195.3	67.2	76.1	23.4	28.5
Productivity Class (By Area)	>8.4 m^3/ha yr (10^6 ha)	19.2	3.7	5.1	1.4	8.9
	5.95 - 8.4 m^3 ha^{-1} yr^{-1} (10^6 ha)	40.0	11.7	19.4	3.0	5.9
	3.5 - 5.95 m^3 ha^{-1} yr^{-1} (10^6 ha)	81.0	25.3	39.8	6.6	9.4
	1.4 - 3.5 m^3 ha^{-1} yr^{-1} (10^6 ha)	55.1	26.5	11.8	12.4	4.4
	Average net Annual Growth (m^3 ha^{-1} yr^{-1})	3.15	2.45	3.99	2.03	3.43
	Potential net Annual Growth (m^3 ha^{-1} yr^{-1})	5.18	4.62	5.39	4.20	6.79
Ownership of Commercial Forest	Federal (10^6 ha)	40.2	4.5	5.8	15.5	14.6
	State, Local, Indian (10^6 ha)	14.7	7.9	1.4	2.0	3.4
	Forest Industry (10^6 ha)	27.9	7.2	14.7	0.9	5.1
	Other Private (10^6 ha)	112.5	47.6	54.3	5.1	5.5
Growing stock and annual growth of commercial forest	Total Growing Stock (vol. %)		24.4	28.4	14.0	23.2
	Net Annual Growth, 1976 (10^6 m^3)	613	164	303	48	98
	Total Growing Stock (10^6 m^3)	20,120				

productivity less than 1.4 m^3 ha^{-1} yr^{-1}; the lower values generally prevail because the sites are very wet, very dry, very rocky, or have adverse climates. Nearly half of the noncommercial forest is in Alaska.

The 195.3 x 10^6 ha of commercial forest in 1977 was down slightly from 201.0 in 1970, 206.2 in 1962, and 202.1 in 1952, and is projected to reach 186.6 by the year 2000. Total growing stock on commercial timberland (in 1977) was 20,120 x 10^6 m^3, up from 17,076 x 10^6 m^3 in 1952, and is expected to increase to 23,690 x 10^6 m^3 by 2000. Demand for timber is projected to increase faster than supply.

A total of 6.6 x 10^6 ha of U.S. commercial forest is classified as unstocked and the fact that much of the remainder is not fully stocked is reflected in the comparison between average and potential net annual growth (Table 10). Potential growth is what could be attained in fully stocked natural stands and is seen to be 65 percent higher than the current average. The difference reflects inadequate stocking, loss due to pests and fires, plus the impact of old-growth stands in the West which do not yield net growth.

The wide differences in productivity are a consequence of differences in soil fertility, species, climate, and elevation--some factors that can be controlled and some that cannot. Note that the lowest productivity class (1.4-3.5 m^3 ha^{-1} yr^{-1}) can be expected to provide less response to intensive timber management than the higher productivity classes. Many nonstocked areas are on sites so poor that attempts to manage and/or regenerate forest would result in very little increase in net annual growth (U.S. Forest Service, 1982). The 1.4-3.5 m^3 ha^{-1} yr^{-1} class often yields important values for grazing, recreation, and other nontimber uses; often in the hilly or mountainous regions of the Appalachians, Ozarks, and Rockies. Productivity on all sites could be increased even more than the potential growth tabulated here by species selection, fertilization, spacing control, use of genetically improved trees, and other intensive management measures.

Much of the net annual growth is taking place in the South where there is a large area of young vigorous forest. Table 11 gives more detail on the geographic distribution of rate of net annual growth and the change over the last three decades. Differences among ownership classes may reflect the nature of the lands owned more than differences in forest management.

The 770 x 10^6 ha of land that comprise the 48 contiguous states contained, at the time of colonization, about 345 x 10^6 ha of "commercial forest" and an estimated additional 40 million hectares of "noncommercial forest." The amount of forest clearing that took place prior to 1800 was very small and the area of commercial forest has been approximately stable since World War I (Figure 4). Clawson (1979) believes that the U.S. has matured as far as land use is concerned and that major changes in land usage are not likely in the future, at least up to the year 2000. "Changes in major land use in the future will be made with more difficulty and will be accompanied with more stresses and strains, public and private, than past shifts in land use" (Clawson, 1979).

Volume of standing timber in U.S. forests has decreased much more than the forest area (see for example, the plot of sawtimber volume in Figure 4). This is partly a consequence of harvesting mature forests and replacing them with young growing forest. One consequence of this decline in standing volume is an increase in net annual growth. Whereas net annual growth was near zero in the pre-colonization forests, this had increased to 170 x 10^6 m^3 yr^{-1} by 1900 and was estimated at 620 x 10^6 m^3 yr^{-1} in 1977 (Clawson, 1979). At least since 1945 annual timber growth has exceeded annual timber harvest in the U.S. (Clawson, 1979).

Clawson (1979) draws four conclusions that are of major significance in the context of this inquiry.

1. "The total area of land in forests in the United States is now largely stabilized." Shifts to and from forest land use will be relatively modest in the future.
2. "The volume of standing timber. . .will continue to increase modestly over the next few decades or longer."

TABLE 11. NET GROWTH PER HECTARE OF GROWING STOCK, ALL SPECIES, COMMERCIAL FORESTS, BY MAJOR OWNERSHIP CLASS, AND BY REGION, 1977.
(m^3 ha^{-1} yr^{-1})

Region	Forest Ownership				
	All	National Forest	Other Public	Forest Industry	Other Private
New England	3.1	3.4	3.9	3.4	2.8
Middle Atlantic	2.7	5.4	3.5	3.2	2.5
Lake States	2.4	2.7	2.3	2.8	2.2
Central	1.8	2.0	2.4	2.0	1.6
South Atlantic	4.1	3.8	3.9	4.3	4.0
East Gulf	4.1	4.0	3.6	3.8	4.3
Central Gulf	4.1	5.4	5.0	4.6	3.9
West Gulf	3.9	3.8	3.2	4.7	3.6
Pacific Northwest Douglas Fir	5.6	2.5	6.5	6.4	7.8
Pacific Northwest Ponderosa Pine	2.3	2.2	2.4	2.5	2.5
Alaska, total	0.8	0.2	1.5	x	1.3
California & Hawaii	3.2	3.2	1.6	4.1	3.0
Northern Rocky Mountains	2.7	2.7	2.7	3.5	2.5
Southern Rocky Mountains	1.2	1.4	0.8	1.3	0.8
All Regions (1977)	3.2	2.5	3.8	4.1	3.2
All Regions (1970)	2.6	2.0	2.7	3.6	2.4
All Regions (1962)	2.2	1.8	2.2	3.5	2.2
All Regions (1952)	2.0	1.6	1.8	3.0	1.9

From Clawson, 1979.

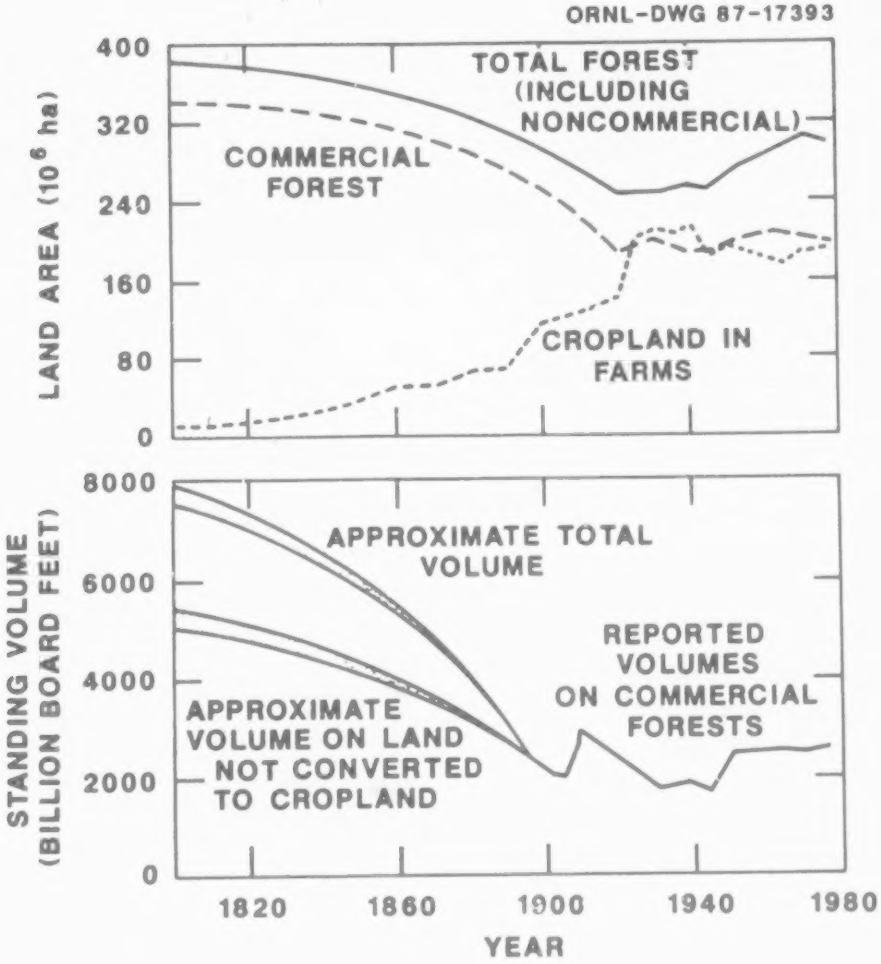


Figure 4. (above) Land in all forests, commercial forests, and cropland in farms in the United States, 1800 to 1975. (below) Standing volume of sawtimber at different dates in the United Sates, 1800 to 1977. From Clawson, 1979.

3. "The trend toward increasing annual timber growth will continue, perhaps accelerate" as a consequence of improved stand management.
4. "The frontier in forestry tomorrow lies at the intensive, not at the extensive, margin of forest practice." Increases in productivity will be largely due to intensive management on the most productive sites.

FOREST GROWTH RATES

The bulk of the literature relating forest clearing to carbon dioxide has been concerned with the rate at which CO_2 is being released. The questions of concern have thus been the rate of clearing, the mass of biologic carbon per unit of land area, the fate of this carbon when the forest is cleared, and the impact of clearing on soil carbon. In contemplating reforestation we are still concerned with the carbon content of the standing crop but of perhaps greater importance is the rate at which that crop can increase in mass, the net annual growth increment.

This text has focused so far on the area of forest land and has presented a pessimistic view of the prospect for significant increases, or even of being able to maintain current areas of forest in the tropics. The competition for land resources for agriculture, biomass fuels, and human infrastructure is very great indeed. We focus now on what Clawson characterized as the "intensive" aspect of forestry, i.e., the productivity of existing forest areas. How fast do forests take up carbon? Is it possible to increase forest productivity so that 5×10^9 tons of carbon can be taken up each year either in existing forests or with some relatively small addition to existing forest area? Information in Tables 10 and 11 begins to answer these questions but integrates over too many variables and does not address what the practical limits might be. Nevertheless, the tables do show that U.S. commercial forests are presently (1977) taking up carbon (based on a crude average of 0.26 tons C per m^3 of wood) at a mean annual rate of 0.82 tons C per ha. The "potential net annual growth" values from Table 10 suggest that, fully stocked, the forests could collect 1.35 tons C ha^{-1} yr^{-1}.

There is a trade-off that needs to be specifically acknowledged. In general, forests with a large standing crop are mature forests with very low (perhaps even negative) rates of net annual growth. Lugo and Brown (1986) note that mature forests can continue to accumulate carbon for remarkably long times (300-1000 years) but this is at very slow rates. There is a measure of incompatibility, then, between storing large quantities of carbon in biomass and maintaining a high rate of carbon uptake. To maintain a high rate of carbon flux to the biosphere via young, vigorous forests implies the harvest and storage of mature trees, perhaps in construction materials. Cooper (1983) reports that if forests are managed for maximum sustained yield of biomass rather than for maximum carbon storage, their carbon content, averaged over the life of the stand, will be about one-third that at maturity. Financially optimized rotations reduce lifetime storage even more.

In the text that follows, we examine the growth rates of existing forests, the variables that affect forest growth rate, and the extent to which management of these forests can lead to increased rates of carbon accumulation in forests. We do not speculate on the harvest and storage of wood. Our concern is with carbon collection in biomass generally, but most particularly in wood. In humid zones more than half of net primary production is allocated to leaf litter production, with relatively short cycle time (Brown and Lugo, 1982). Farnum et al. (1983) estimate that, in general, maximum net primary productivity may be 2-1/2 times maximum mean annual growth increment.

Although the volumes and ages will be different for different species and environments, the general pattern of forest tree growth is as shown in Figure 5. The figure illustrates the early maximum in leaf area and net annual production compared to the long-term accumulation of total biomass. Figure 6 shows the typical pattern for buildup in the various forest components and illustrates again that carbon uptake is at its highest rates in young, vigorous forest. So long as harvest does not occur, considerable carbon accumulation continues to take place in litter, soil organic matter, and the below ground portion of

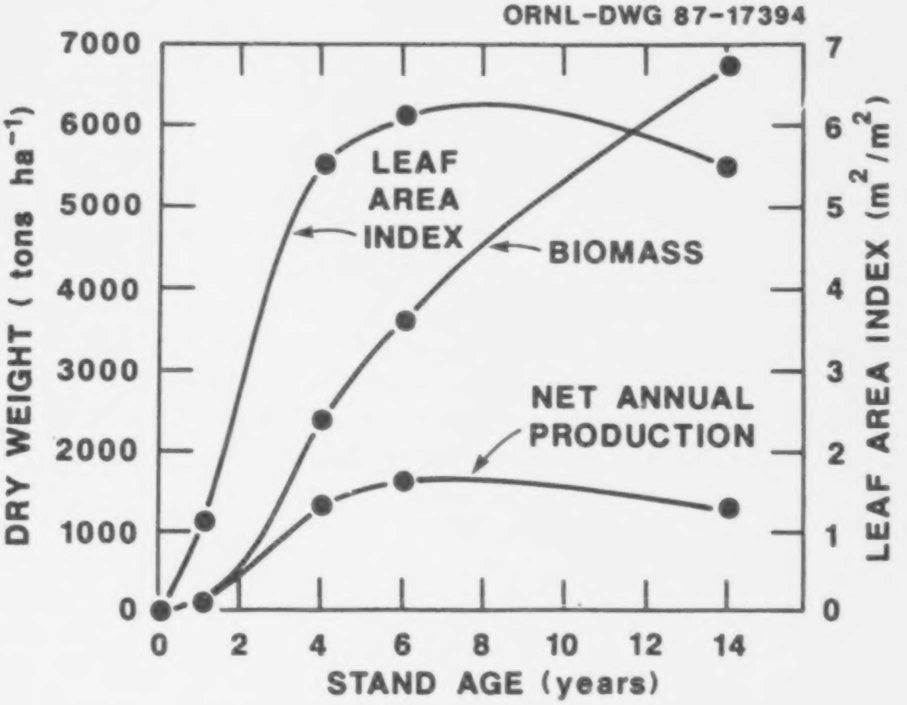


Figure 5. Relationships of biomass, net annual production, and leaf area index to stand age. From Marks and Bormann, 1972.

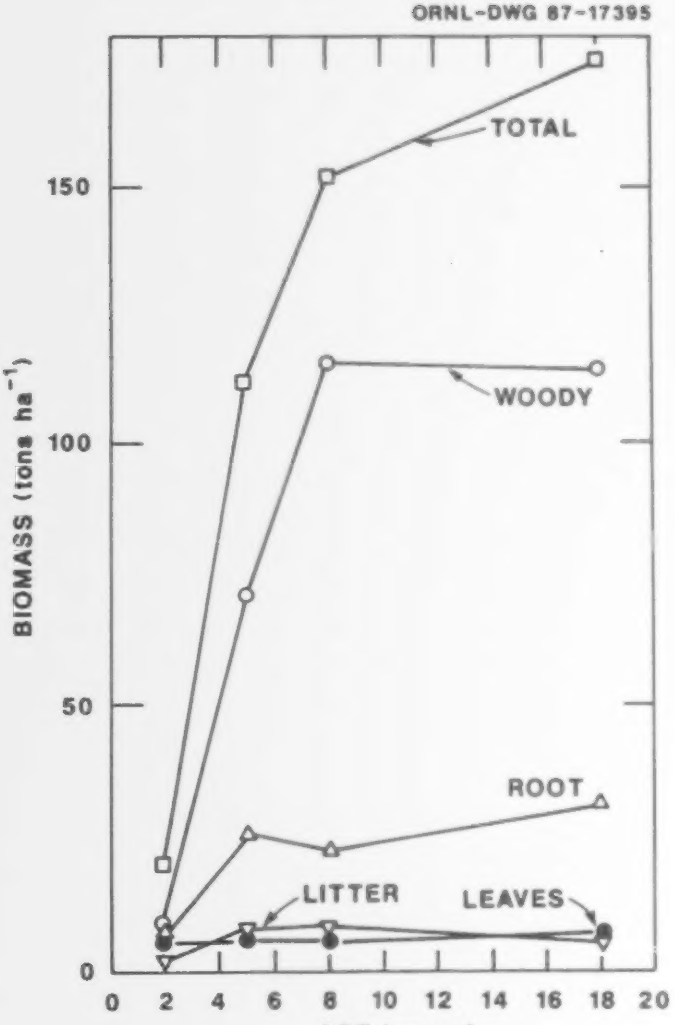


Figure 6. Relationship between biomass of forest components and stand age in a Tropical Moist Forest Life Zone. From Brown, 1980.

trees. (The accumulation and storage of detrital and soil carbon are strongly dependent on stand composition and climate [see e.g. Cooper, 1983]). Although the total rate of accumulation of carbon in forests needs ultimately to include the accumulation of carbon in forest soils, emphasis here is on carbon in the woody parts of trees. This will be especially appropriate if we are envisioning forest management for maximum net annual carbon uptake rather than for maximum carbon storage.

To visualize carbon uptake in trees we need to establish numerical averages for conversion of the generally available data on timber volume. The density of wood varies over a limited range and when averaged over a mixed forest the range becomes even smaller. Brown and Lugo (1984) used 0.57 - 0.62 gm/cm^3 for tropical broad-leaved forests and 0.45-0.52 for tropical coniferous forests, with differences between continents. Armentano (1984) used 0.438 gm/cm^3 for U.S. softwoods and 0.525 for hardwoods. Delcourt and Harris (1980) used 0.517 for the eastern U.S. as a whole. Unless otherwise stated, we use 0.52 gm/cm^3 as a mid-range conversion factor in our estimates. A lower value might be appropriate for young plantation material. Houghton et al. (1985a) report that the fractional carbon content of wood varies between 0.47 and 0.52 of the dry mass. Delcourt and Harris (1980) used 0.496. Like many other authors (e.g., Brown and Lugo, 1982) we use 0.50. Using both of these factors would suggest that 1 m^3 of timber represents approximately 0.52 dry tons of wood or 0.26 tons of carbon (1 ton = 10^{3}kg).

Selection of a simple multiplier for translation from stemwood biomass to total biomass is not so straightforward. After evaluation of the literature, Brown and Lugo (1984) chose 1.6 for closed tropical forest and 3.0 for open tropical forest. Johnson and Sharpe (1983) noted that the relationship changes with species composition and decreases with increasing stand size class. They chose 2.6 to represent the eastern U.S. and suggested the value for the western U.S. would be only slightly smaller with full accounting. Brown et al. (1986) likewise showed an age dependence (in keeping with the basics of

Figure 7), with values declining from 1.8 for stands less that 5 years old to 1.4 for stands with age greater than 20 years. Values used in the literature range from less than 1.3 to over 3.0, depending on the forest type and completeness of the accounting. We have evaded this question by choosing to examine stemwood biomass, but if our focus were more on long-term accumulation of standing biomass, this would become an important factor.

The question, then, is the rate at which the standing stock of forests increases in mass--the productivity or mean annual increment-and, ultimately, how this value might be increased. The ability of forests to accumulate and store carbon varies greatly. Data in Brown and Lugo (1982) show large variation in the mass of organic matter per hectare for tropical and subtropical forests (40-538 tons ha^{-1} plus 24 - 599 tons ha^{-1} of soil carbon). (See also Figure 7). They also show net primary productivity varying between 11.1 and 20.8 tons ha^{-1} yr^{-1} and wood production from 0.9 to 11.2 tons ha^{-1} yr^{-1}. Standing crop biomass of many mature temperate forests seems to center on 200-300 tons ha^{-1} (Cooper, 1983), although both higher and lower values are widely reported. Brown and Lugo (1982) believe that in large measure the production and storage of organic matter show a predictable relationship with climatic zone. Zavitkovski and Isebrands, (1983) describe a decrease in biomass productivity with increasing latitude.

We have seen that U.S. forests are categorized according to "productivity class" with commercial forest subdivided into categories from 1.4 to greater than 8.4 m^3 ha^{-1} yr^{-1} of timber production (see Table 10). Holowacz (1985) reports a mean net annual increment for the huge forest area of the U.S.S.R. of only 1.14 m^3 ha^{-1} yr^{-1}, the low value partly a result of poor soil and climate conditions but also a consequence of large areas of mature to over-mature forest. (We have already shown that the mean annual growth for the U.S. is largest in the South where there are large areas of young vigorous forest.)

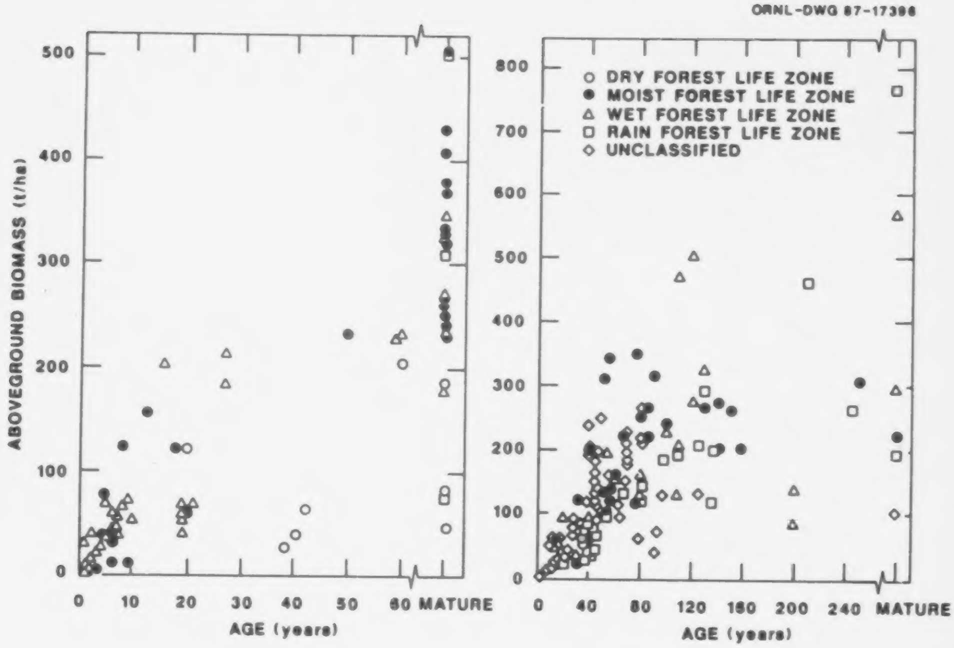


Figure 7. Relationship between above-ground biomass in temperate (left) and tropical (right) forests and stand age. From Brown and Lugo, 1982.

Current values for other areas are shown in Table 12. (Recent estimates of carbon stocks have been decreasing [Houghton et al, 1985a].)

The growth rate of trees is a consequence of stand and site attributes: species, structure, water and nutrient availability, climate, and silviculture practices. Borough et al. (1984) summarized yield statistics for many species of eucalyptus. They found values for mean annual increment as high as 35.0 m^3 ha^{-1} yr^{-1} for plantations on moist sites in Tasmania. Values greater than 20.0 m^3 ha^{-1} yr^{-1} were common. At the same time natural stands were reported with growth rates as low as 1.2 m^3 ha^{-1} yr^{-1}. Teak in India has been measured to have a mean annual increment of 2.5 m^3 ha^{-1} yr^{-1} but on optimum sites in Trinidad can reach 13 m^3 ha^{-1} yr^{-1} (FAO, 1985a). While high growth rates (up to 60 m^3 ha^{-1} yr^{-1}) occur in the tropics, not all tropical tree species have high growth rates. River red gum yields 30 m^3 ha^{-1} yr^{-1} in wet areas but only 5-10 m^3 ha^{-1} yr^{-1} in dry areas (Bowen and Nambiar, 1984). Very high-yielding plantations of eucalyptus usually occur where the total annual precipitation is at least 800 mm (Turnbull and Pryor, 1984).

The potential is clearly much greater than current experience. The "potential" figure for the U.S. (Table 10), for example, is based on fully stocked natural stands. Namkoong (1986) writes of a 4-year-old forest in Brazil producing at a rate of 45 m^3 ha^{-1} yr^{-1}. Marks and Bormann (1972) describe pin cherry in temperate environments with mean annual growth at 6 years near 16 m^3 ha^{-1} yr^{-1} and American sycamore can be grown in short rotation in Georgia with CO_2 uptake equivalent to a net annual growth as high as 26 m^3 ha^{-1} yr^{-1} (Steinbeck and Brown, 1976). The point is that net annual growth can be very much higher than at present if fast-growing species are grown with advanced silviculture techniques on optimum sites. Silviculture practices can include species selection, genetic screening, spacing, thinning, pruning, weed control, fire and pest control, fertilization, irrigation, harvest cycle time control, site preparation, etc.

TABLE 12. MEAN NET ANNUAL GROWTH FOR CURRENT COMMERCIAL FOREST AREAS

	Net Annual Growth (m^3 ha^{-1} yr^{-1})[1]	Reference
U.S. - 1977 Average	3.15	U.S. Forest Service, 1982
Potential	5.18	U.S. Forest Service, 1982
China	1.5	Smil, 1983
Canada	1.7	Holowacz, 1985
U.S.S.R.	1.14	Holowacz, 1985
Europe	3.3	
Nordic Countries	2.7	
EEC Countries	3.6	
Eastern Europe	4.1	FAO, 1976
Swedish Pine	3-4	Bowen and Nambiar, 1984
U.S. Non-Commercial Forest	0.7	Armentano, 1984
Tropical Moist Forest	6-15	from data in Brown and Lugo, 1982

---

[1] For comparison with other tables, an approximate conversion to tons ha^{-1} yr^{-1} can be achieved by multiplication by 0.52.

Growth rate can be optimized in managed stands or plantations and Nambiar (1984, p. 5) argues persuasively that "There is no doubt that the future supply of wood and the maintenance and restoration of the quality of the environment is very strongly dependent on development of forest tree plantations."

Armentano (1984) suggests that doubling the U.S. 1970 growth levels represents the biological potential. Brown (1976) writes of multiplying U.S. yield of wood by 10 to 15-fold with existing technology. According to Farnum et al. (1983), "Silviculture and genetic manipulation of Douglas fir and Loblolly pine plantations have increased their productivity 70 and 300 percent, respectively, over natural forests on the same sites, yet these intensively managed plantations are achieving less than 50 percent of their potential productivity. Future increases in yield will result from optimization of nutritional treatments, control of noncrop vegetation, and advances in tree breeding and tissue culture techniques." Hansen (1987) reports that production increases of 3-5 times have already been attained over the last 20 years by applying agronomic principles to forest plantations. Fire suppression in many parts of the world may already be boosting carbon stocks and permitting forest expansion into grass lands (Houghton et al., 1985a).

For contrast with the growth rates of existing forests, Table 13 provides some data on the growth rate of wood in managed forests. In Table 14 the rates of growth of managed and unmanaged stands of two species are contrasted. Farnum et al. (1983) emphasize the importance of interactions among treatments.

To see the possibilities for the cumulative impact of advanced silviculture techniques, the extremely high productivities achieved in short rotation, intensively cultured plantations (Ranney et al., 1987) are instructive even though they have not been sustained over extended periods. Zavitkovski and Isebrands (1983) report eucalypts with maximum production up to 29.6 tons ha^{-1} $yr,^{-1}$ although this is for total biomass and 13.0 tons ha^{-1} yr^{-1} was their highest reported

TABLE 13. GROWTH RATES OF STEMWOOD IN SOME MANAGED FORESTS AND PLANTATIONS

Forest Region or Type	Stemwood[1] (m^3 ha^{-1} yr^{-1})	Rotation (yr)
UK average (conifer Plantations)	10.0-	40-65
New Zealand and Australia (radiata pine)	18.0-35.0	20-50
Sub-tropical eucalyptus	5.0-30.0	8-25
Tropical high forest (managed)	0.5-7.0	
SE Asia dipterocarp forest (managed)	4.5-17.0	70-100
Malaysian dipterocarp plantations	4.5-9.0	18-45
Tropical pines	15.0-45.0	8-30
Tropical hardwood plantations	25.0-35.0	8-20
Tropical eucalyptus	18.0-60.0	7-20

From Nambiar[1984].

[1] For comparison with other tables, an approximate conversion to tons ha^{-1} yr^{-1} can be achieved by multiplication by 0.52.

TABLE 14. PRODUCTIVITY INCREASES ATTRIBUTABLE TO INTENSIVE PLANTATION MANAGEMENT

Case	Maximum Mean Annual Yield (Tons ha^{-1} yr^{-1})
Douglas Fir in Washington	
Natural stands	5.7
Silvicultural treatments	
Plantation establishment	7.2
Nitrogen fertilization	8.8
First-generation genetics	9.7
Target	25.0
Loblolly Pine in North Carolina Pocosins	
Natural stands	3.6
Silvicultural treatments	
Drain and plant	7.0
Bedding	8.6
Preplant phosphorus	10.5
Nitrogen fertilization	11.8
First- and second-generation genetics	14.3
Target	30.0

From Farnum et al. (1983)

value for stemwood biomass in short rotation, intensively cultured plantations. Heilman and Stettler (1985) used hybrid cottonwoods on fertilized, irrigated plots to achieve up to 27.8 tons ha^{-1} yr^{-1} of total biomass production in Western Washington. Short rotation forestry is not a panacea for CO_2 control. Cropper and Ewel, 1987, have calculated that converting forest land in northern Florida to slash pine biomass plantations with an 8-year rotation would release to the atmosphere 35-40 percent of the carbon currently stored in the forests because of the smaller mean standing crop and depletion of soil carbon.

The role and potential role of forest fertilization are still open to discussion. Although fertilization can produce dramatic impacts on productivity, the economics are less certain. A standard reference work (Stoddard and Stoddard, 1987, p. 98) tells us "it is not clear through research whether chemical fertilizers are economical to use--that is, whether their costs are equal to or exceed the value of the growth increase." Binkley, (1986, p. 108), however, suggests "the economics of forest fertilization can be very attractive" and that more than half of the Loblolly pine plantations in the southeastern U.S. would respond profitably to fertilization. Ford (1984, p. 18) believes "Fertilization is the most important single treatment that the forest manager can apply during the growth of the crop to accelerate growth." Much remains to be learned.

Spectacular results have been reported in response to fertilization. Nambiar (1984) highlights experiments showing significant responses over large areas, in older stands, and in cold environments. Additions of N and P increased net primary production in Tasmania blue gum by over 100%. Responses in excess of 200 m^3 ha^{-1} over a rotation have been obtained following phosphorous fertilization (Ballard, 1984). Bevege (1984) summarizes growth rate increases of up to 80% in response to fertilization.

Hyde and Wells (1979) assume 70% increases in productivity in response to fertilization. Fertilization can reduce rotation length by years, produce higher values of mean annual increment, and produce an earlier maximum in mean annual increment (see, e.g., Figure 8). Chemical fertilizers will stimulate growth for periods up to 10 to 12 years (Stoddard and Stoddard, 1987) and a single phosphorous application may suffice for an entire rotation (Farnum et al., 1983).

Table 15 shows the distribution of four nutrient species and total biomass among the major tree parts for five species of mature trees. As seen in Table 15, there are significant species differences in tissue nutrient concentration. The extent to which fertilization is required depends also on the nutrient status of the initial site and, in plantations, on the rate at which nutrients are removed with the harvested crop. If leaves and small branches are left on site their nutrient content will be retained in the ecosystem.

One of the obstacles is that recovery rates of fertilizer nutrients by trees are generally low (Ballard, 1984). Leaching, microbial activity and volatilization can lead to major losses. Also, harvest of nutrients with the trees can be important, especially in the tropics where a larger fraction of the total available nutrient supply resides in the trees as opposed to in the soils and surface litter. Characteristics specific to each site will be very important in determining the response to chemical fertilizers.

Optimization of expensive nutrient additions is critical to their successful application. In one study, Bevege (1984) showed that 47 Kg ha^{-1} of superphosphate produced a 90% increase in total stand volume at age 11 but twice the phosphate application resulted in no further volume increase. We also need to exercise some care in where fertilizer is applied. Bevege (1984) reminds us that the absolute gain by fertilizing a good site may be more important than the larger relative gain on a poor site, e.g., our interest is increased absolute output.

Part of the fertilizer problem may be addressed by considering legumes, as many forests respond extensively to nitrogen treatment alone (Ballard, 1984). There are many woody plants that are legumes,

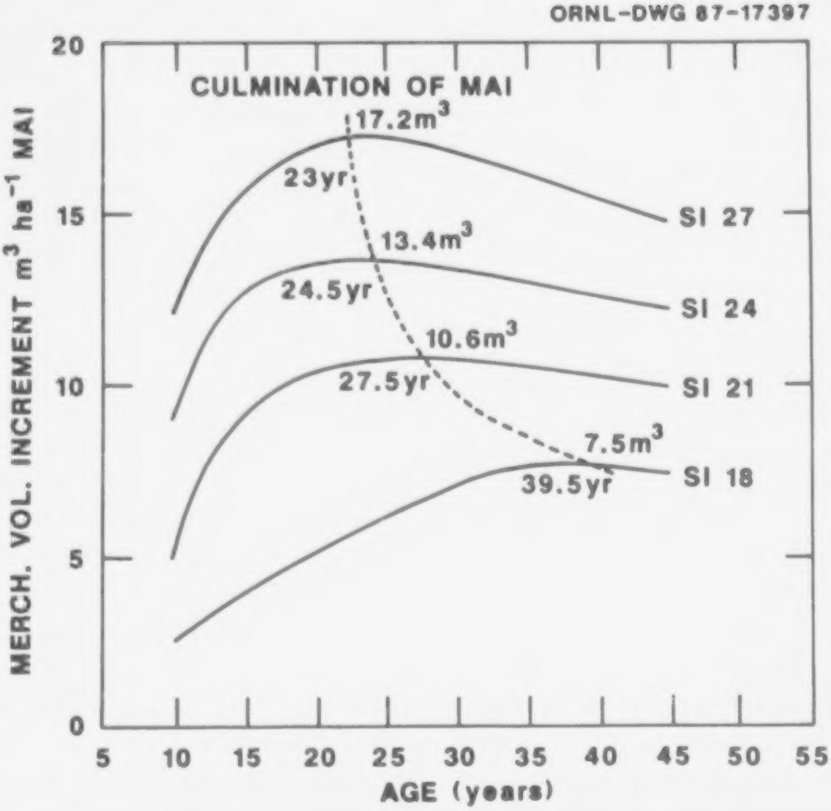


Figure 8. Influence of site quality, measured as site index (S.I.), and age on merchantable volume increment in *P. elliottii*. Although site index is a combination of site factors of nutrition, water, and soil profile characteristics; in these stands fertilization with 47 Kg P ha^{-1} as superphosphate raised the site index from 22.8 to 27.6. From Bevege, 1984.

TABLE 15. NUTRIENT DISTRIBUTION WITHIN MAJOR PARTS OF THE TREE AS A PERCENT OF TOTAL CONTENT, TOTAL NUTRIENT CONTENT AND BIOMASS OF FIVE SPECIES.

Species	Age (yr)	Foliage (%)	Branches (%)	Bole Bark (%)	Bole Wood (%)	Roots (%)	Total (kg ha^{-1})
				N			
Pinus sylvestris	45	30	20	11	20	19	186
Picea glauca	40	34	28	10	13	15	449
Pseudotsuga menziesii	36	32	19	15	24	10	320
Betula verrucosa	55	14	31	--	27	28	543
Quercus alba	150	9	23	--	36	22	631
				P			
Pinus sylvestris	45	27	19	14	11	29	21
Picea glauca	40	42	27	13	8	10	64
Pseudotsuga menziesii	36	44	19	14	14	9	66
Betula verrucosa	55	12	35	--	32	21	34
Quercus alba	150	10	19	--	30	35	41
				K			
Pinus sylvestris	45	27	17	13	19	24	96
Picea glauca	40	34	31	12	13	10	254
Pseudotsuga menziesii	36	28	17	20	24	11	220
Betula verrucosa	55	22	23	--	32	23	200
Quercus alba	150	14	31	--	27	26	419
				Ca			
Pinus sylvestris	45	13	19	21	28	19	123
Picea glauca	40	32	27	20	10	11	809
Pseudotsuga menziesii	36	22	32	21	14	11	333
Betula verrucosa	55	6	28	--	42	24	651
Quercus alba	150	3	33	--	39	20	2,029
				Biomass (t ha^{-1})			
Pinus sylvestris	45	4.4	10.6	5.3	55.6	19.3	95.2
Picea glauca	40	17.4	34.6	10.8	88.0	34.0	184.8
Pseudotsuga menziesii	36	9.1	22.0	18.7	121.7	33.0	204.5
Betula verrucosa	55	2.5	28.7	--	134.5	49.8	215.5
Quercus alba	150	5.4	52.8	--	129.0	95.6	282.8

From van den Driessche, 1984.

e.g., black locust, and honey locust in North America. Leucaena has been observed to grow to 6 m in its first year, and calliandra (a leguminous bush) sprouts from stumps, can be cut on a 1-year rotation, and can reach 5 to 6 m in a single year (Vietmeyer, 1986).

Genetic selection is another vehicle for increasing forest yield. There is evidence for genetic variation in rate of carbon fixation and net photosynthesis in forest trees (Bevege, 1984). Gains in wood volume of 8-23% in 1.0 - 1.5 generation in pines and even greater improvement in eucalyptus have been reported (Nambiar, 1984). Within tree species there is genetic variation to nutrient availability, i.e., the adaptability to nutrient deficiency (Goddard and Hollis, 1984). In closed-canopy coniferous forest, light absorption is more efficient than in agricultural crops, yet the photosynthetic rates of single leaves in trees are only about half those in agricultural crops under similar conditions (Farnum et al., 1983). Might these variables be subject to manipulation?

Tree improvements through selection and cloning can be anticipated in the areas of growth rate, wood quality, disease and pest resistance, drought tolerance, use of mineral nutrients, allocation of photosynthate and geographic adaptability (see, for example, Farnum et al., 1983; Gerhold et al., 1986). One of the current concerns over the clearing of tropical forests is to ensure genetic diversity so that we can have options for pursuit of new economic goals, adaptation to changes in site or climate, and for survival within the community of pests, pathogens, and competitors. The genetic resource needs to be adequate to be able to respond to changes in objectives (Namkoong, 1986). Vietmeyer (1986) points out that while there are thousands of different tropical tree species, 87% of tropical forestry employs only 3 tree types (pine, eucalyptus and teak). This is true even in temperate latitudes; in the Soviet Union there are 570 species of trees but only 30 of major economic significance (Holowacz, 1985).

Bevege (1984) has described what the upper limits to productivity might be. After discussing optimum conversion efficiencies for solar energy to biomass, the upper limits for gross primary productivity and the effectiveness of formation of the desired components of the crop, he estimates that "an economic fibre yield of about 87 tons ha^{-1} yr^{-1} as wood would be a reasonable upper limit for fibre production over a wide range of species and environments" (Bevege, 1984, p. 296). On the assumption that an ultimate upper bound of annual per hectare production is set by the quantity of incident solar radiation, Hyde and Wells (1979) suggested 54.8 tons ha^{-1} yr^{-1} is that upper bound. This latter limit is being approached by intensively cultured tree plantations and Bevege (1984) cites an actual yield for Napier grass at 88 tons ha^{-1} yr^{-1}.

FURTHER THOUGHTS

Additional factors that have to be confronted when envisioning tree growth are related to unintentional future changes in the tree's environment. What will be the impact on trees as CO_2 increases, as the climate changes, as the concentration of other environmental chemicals changes (e.g. acid rain, heavy metals, and photochemical oxidants). There is already widespread concern about tree damage in central Europe (e.g., Postel, 1984) and there is evidence that both individual trees and whole stands in the southeastern U.S. are growing more slowly than they did 20 to 30 years ago (Sheffield and Cost, 1987). Recent data suggest that diameter growth rates for yellow pines on natural stands throughout the southeast have dropped 30-50 percent over the last 30 years and loblolly pines in Georgia have behaved similarly. Many believe the cause may be atmospheric deposition but other factors such as drought and increasing stand density may be playing a role. Major areas of oak forest in the forest-steppe region of European U.S.S.R. have deteriorated due to air pollution (Holowacz, 1985).

If the atmospheric carbon dioxide concentration doubles and brings the predicted changes in climate, what impact will this climate change have on tree productivity? Models of the effect of CO_2-induced climate change suggest increases in carbon storage in Canadian boreal forests, although not large enough to compensate for large decreases in carbon storage in eastern U.S. forests (Trabalka et al. 1985). The net global impact could be very important. Houghton et al. (1985a) have observed that although the response of terrestrial systems to changes in climate could dwarf the fluxes from changes in land use, ecologists are not in agreement about the direction of the climate response.

And what about the increasing CO_2 itself? There is a vast literature on the effect of elevated CO_2 concentrations on growing plants. The initial presumption is that because CO_2 is a plant nutrient, increased atmospheric CO_2 will accelerate plant growth. On the other hand it is sometimes argued that CO_2 is seldom the limiting nutrient and that the effect will be minimal.

For woody plants, dry weight, stem diameter, height, branching, and leaf area all have been shown to increase with CO_2 concentration, at least to 700 ppm (Kimball, 1985). LaMarche et al. (1984) believe that upper treeline conifers may be already showing CO_2 induced growth (for reservations, see also Wigley et al. 1984). Strain and Armentano (1982) believe it reasonable to assume that photosynthesis will increase but that it is less certain what will happen to the increased photosynthate.

Moving from experimental growth responses of seedlings and agricultural crops to forests is a major leap. Despite the extensive literature showing growth enhancement in growth chambers, Solomon et al. (1984, p. 73) write, "there is yet no evidence that any life stage of forest trees beyond seedlings will benefit from CO_2 fertilization, as apparently will plants in noncompetitive and nonlimiting agricultural systems."

In the summary to an extensive review of the data on CO_2 growth enhancement, Strain and Cure (1985) suggest that the preindustrial level of atmospheric CO_2 was "almost certainly" a limiting factor in agricultural productivity. Estimates of growth enhancement in agricultural systems are uncertain, but range from 0.5 to 2.0% for each 10 ppm increase of atmospheric CO_2 (Strain and Cure, 1985). There is little empirical information, however, on native species. Although estimates of the magnitude are not now possible, the prevailing view seems to be that total community biomass will increase with increasing atmospheric CO_2 (Strain and Cure, 1985). There is, in fact, only one region where there are experimental data to demonstrate that increased atmospheric CO_2 will lead to increased carbon sequestering-- the arctic tundra (if temperature and soil-water level are unchanged)-and even those data are not without ambiguity (see Oechel and Strain, 1985 and Hilbert et al., 1987).

It should be pointed out in closing this section that there are other measures within the biosphere that can lead to reduced pressure on atmospheric CO_2. Wilson (1978) reminds us that there are agricultural practices to remove CO_2 from the atmosphere. Conversely Armentano and Menges (1986) describe the loss of a carbon sink with drainage of temperate zone organic soil-wetlands. Olson et al. (1985) estimated current carbon accumulations in wetlands, including bogs, could be on the order of 1×10^9 tons C yr^{-1}. Smith (1981) discusses CO_2 uptake by marine macrophytes. Dyson and Marland (1979) contemplated cultivation of fast growing aquatic plants such as water hyacinth and Broecker (see Dyson and Marland, 1979) raised the possibility of fertilizing marine algae. All of these approaches involve much smaller quantities of carbon per unit area and/or much higher demands on other nutrient elements than do trees.

Peterson and Melillo (1985) have examined the extent to which eutrophication of the biosphere may be now providing a biospheric sink for carbon dioxide, that is, the extent to which man-induced changes in the geochemical cycles of nitrogen and phosphorous may be leading to increased carbon storage in forests, coastal oceans, and the open sea. Their conclusion is that 0.2×10^9 tons C yr^{-1} is an upper limit for this process because the C:N and C:P ratios in the CO_2 sources (fossil fuels, and mature forests) are so much greater than the ratios in the sinks (regrowing forests and aquatic sediments). Because early successional forests and aquatic plants have lower C:N and C:P ratios than mature forests, by cutting mature forests we are decreasing the carbon storage on land and releasing nutrients to downstream ecosystems which store less carbon per unit of nitrogen and phosphorous than do the mature forests (Peterson and Melillo, 1985). Nitrogen loading of forests as a consequence of fossil fuel burning has the potential to lead to storage of 97.0 x 10^6 tons yr^{-1} of C in forests (Peterson and Melillo, 1985). (See also Baes et al., 1985)

THE PROSPECTS FOR LARGE-SCALE PLANTATIONS

The evidence accumulated here shows that forest growth rates considerably greater than current averages are not only possible but are to be expected. Increased growth rates, however, will probably be accompanied by smaller masses of standing stock. The best prospects for high growth rates are in young vigorous plantations and other intensively managed forests. In fact, many observers believe that in the case of global firewood, the creation of new resources through plantations is in the long run essential (see e.g., de Montalembert and Clement, 1983). The problem, as we have noted, is the lack of available land where conditions are favorable to forest plantations. It was generally the need for arable land that led to deforestation initially.

To contemplate reforestation, the U.S.S.R. has both the largest land area and the largest area of closed commercial forest. Most of their 810.9 x 10^6 ha of forest (Holowacz, 1985), however, is in the boreal forest zone with relatively slow growth rates as a consequence of the severe climate and poor soils. In addition, 60 percent of the growing stock is estimated to be mature or over-mature and hence has small annual growth increments. There are, however, an estimated 252 x 10^6 ha of non-forested but potentially productive forest land. Holowacz (1985) suggests, these are probably burned areas remote from the existing forest fire protection network. A 1984 forest inventory suggested 2/3 of this land was in need of a major undertaking to secure a forest cover. The mean annual growth increment for the U.S.S.R ranges up to 3.62 m^3 ha^{-1} in the Ukraine but averages only

1.14 m^3 ha^{-1} for the entire country. Holowacz (1985) estimates the annual increment could be boosted 50 percent (from 931 x 10^6 m^3 yr^{-1} to 1400 x 10^6 m^3 yr^{-1}) if there was a normal age class distribution and adequate regeneration of unstocked areas. The U.S.S.R. has 16.9 x 10^6 ha of forest established by man and is adding 2.2 x 10^6 ha yr^{-1} (by contrast annual clearcut is currently estimated at 2.1 x 10^6 ha yr^{-1}).

Pearse et al. (1986) remark on 1.3 x 10^6 ha of forest land in British Columbia, Canada, that is not satisfactorily restocked. In Europe there is a high degree of uncertainty about the availability of land for reforestation and the extent to which wood supply can really be further expanded. In Europe, 4 percent of the land area is described as "poorly stocked other wooded land" (FAO, 1976). Schooley et al. (1979) and others have tried to inventory U.S. land available for tree "energy farming." On a global scale one can try to tabulate areas available to be reforested, but in large measure they are areas where productivity is low in relation to our concept of atmospheric CO_2 removal.

Vidyasagar (1986) points out that if a vegetarian diet were widely adopted, there would be a great deal of land available for reforestation. He claims only 60 percent of the land presently under cultivation would be required to support the current human population if it were fed directly on grain rather than via the inefficient path of grain-fed meat. If his figures are correct, this would release 600 x 10^6 ha of arable land for reforestation. Conversely, if greater consumption of animal products were to occur in the developing countries, there would be increased demand for grain and agricultural land (Barr, 1981).

Success with tree plantations to data has been considerable but at nothing approaching the scale discussed in this paper. In Table 5 I presented Lanly's (1982) estimate of the area of tropical tree plantations (11.5 x 10^6 ha at year-end 1980 with a current rate of 1.1 x 10^6 ha yr^{-1}). Brown et al. (1986) have broken down their estimate of 11.1 x 10^6 ha according to age and show 60 percent of this area was planted in the last decade. Brown et al. estimate that these 11.1 x 10^6 ha of tropical plantations are currently taking up CO_2 at 0.03 - 0.11 x 10^9 tons C yr^{-1}. If their upper limit is correct, it would require about 500 x 10^6 ha to collect our target 5.0 x 10^9 tons C yr^{-1}. The suggested upper bound for the mean annual volume increment for these plantations (9.6 tons C ha^{-1} yr^{-1}) is fairly high because of the low mean age (it peaks at 13.5 tons C ha^{-1} yr^{-1} for the 6-10 year age class.)

Computations so far in this text have thus shown that if plantations could be managed with the current mean annual growth increment of the best tropical plantations, 500 x 10^6 ha of new plantations would be required to remove CO_2 from the atmosphere at a rate roughly equivalent to the current fossil-fuel burning releases. Similarly, at growth rates comparable to the best of American sycamore plantations on short rotation in Georgia, 700 x 10^6 ha of new plantations would be required. An alternative to envisioning this magnitude of new forest area would be to stimulate accelerated growth uniformly over the entire 3000 x 10^6 ha of existing closed forests. The required growth increment would be 1.7 tons C ha^{-1} yr^{-1} over this entire area. This number is, in fact, three times the difference between the current and potential net annual growth rates for all U.S. commercial forest as taken from the U.S. Forest Service (Table 10). Of course, the nearer we can approach the kinds of extreme growth rates achieved on plantations and discussed above, the smaller the area over which the treatment would need to be applied. These calculations assume too, that additional clearing of forests does not occur.

Before continuing in this vein, it is worth confronting two additional issues, the use of wood (i.e., for fuel) and the institutional demands of large-scale forestry. When fuelwood is used in a true sustained-yield mode, there is no net discharge of CO_2 because the growing trees take in quantities equivalent to what is being released by burning. There is also no net CO_2 uptake. To the extent that wood fuel can replace fossil fuel, the growing wood will act to restrain further growth in atmospheric CO_2. One problem, as pointed out earlier, is that forests managed for maximum mean annual increment and maximum CO_2 uptake are young, vigorous forests with small standing crop. For forest growth to be effective in removing fossil-fuel CO_2 from the atmosphere for periods longer than the period of near maximum growth rate, the wood must be harvested and either used to replace existing fossil fuel burning or stored in such a way that the wood does not oxidize back to CO_2. The current concern remains that the converse is still happening. de Montalembert and Clement (1983) write of areas where insufficient availability of fuelwood will require substitution of commercial fuels.

Rotty (1986) reports that in 1983 0.50×10^9 tons C were released as a consequence of using wood as a fuel. Another 0.17×10^9 tons C were stored in wood harvested for lumber, poles, etc., and will be released to the atmosphere only over long times. Worldwide the 1983 wood harvest exceeded 3000×10^6 m^3 with 54 percent for fuelwood, but the fuelwood fraction goes as high as 88 percent in Africa and as low as 16 percent in Europe (Rotty, 1986). It has been suggested that with intensive management, the U.S. could meet 12 percent of its energy needs with wood (this does not charge for the energy required for fertilizer production or forest management) (Armentano and Hett, 1980).

The challenge of large-scale forestry is technical but also social and economic. The attitude of local populations has been repeatedly cited as a challenge of reforestation (e.g., Shiva, et al., 1985). In discussing supplies of fuelwood in developing countries, de Montalembert and Clement (1983) remark (p. 104), "People do not seem concerned by or interested in plantations in the form of blocks of a certain size, immobilized for forestry use for a long period of time, about which they have not been consulted and the yield from which will not provide them with any direct, substantial and equitably divided benefits. At best the most that can be expected is a passive attitude; often there is more or less open hostility, resulting in illegal felling and degradation." The active participation of people is indispensable to the success of reforestation programs (de Montalembert and Clement, 1983). Smil (1983) blames the poor success of plantations in China at least partially on the failure of support and participation by the peasantry. Shiva et al. (1985) note similar problems in India. Foresters speak of "social forestry" and the necessity of multipurpose forests. de Montalembert and Clement (1983, p 120) conclude that if large scale reforestation for fuelwood is "to be successful and sufficiently massive to attain the impact required, it is indispensable to train personnel, strengthen structures, intensify applied research, instill new capacities for development and new enthusiasm in the populations concerned."

Large-scale, intensive forestry at the scale discussed can also be very expensive. de Montalembert and Clement (1983) note that FAO and World Bank studies from 1981 both suggest that the establishment and tending of large-scale plantations in the Sahelian region required well over $ US 1000 per hectare for an expected yield of 4 - 7 m^3 ha^{-1} yr^{-1}. Data for teak plantations in Trinidad show a requirement of 100 man days ha^{-1} for plantation establishment up to and including the first thinning (6 years) (FAO, 1985b). de Montalembert and Clement (1983, p. 23) worry that the cost of plantations just to supply fuelwood in developing nations "might well endanger the development potential of the countries concerned." Trimble is cited as being concerned that the reforestation of the southeastern U.S. is consuming large quantities of water and negatively impacting water supply (Los Alamos National Laboratory, 1987).

CONCLUSION

The question, finally, is whether it is technically and politically reasonable to envision taking up enough CO_2 in biomass to counter the CO_2 discharged by fossil fuel burning. Having released, over the last 100 to 200 years, perhaps 120 x 10^9 tons of carbon from the biosphere, can we put carbon back into the biosphere at a rate approaching 5 x 10^9 tons yr^{-1}? Can we replant all forests ever cleared with species growing at the rate of American sycamore plantations on four-year rotation in Georgia? Can we create 500 x 10^6 ha of forest with growth rates comparable to that of the best forest plantations in the tropics? Can we envision the application of silviculture practices that would increase the mean annual increment of the world's closed forest by 1.7 tons C ha^{-1} yr^{-1} (6.5 m^3 ha^{-1} yr^{-1} of stem wood)? In Table 16 we present additional possibilities for area and forest growth rate that accomplish an annual uptake of 5 x 10^9 tons C--a rate of uptake that would in 18 - 36 years return to the biosphere all of the carbon that has been released over the last 100 to 200 years (Houghton et al., 1985a). For the last case in Table 16, I have used the data of Table 2 to show the implications of suggesting that each country deal with its own CO_2 discharges.

The most attractive case shown seems to be the one with 2/3 of 5 x 10^9 tons C taken up in the stemwood of closed tropical forests and 1/3 in the stemwood of closed temperate forests. A comparison of Tables 16 and 12 reveals that what we are envisioning in this case is roughly doubling the mean annual volume increment of the world's existing closed forests. The required growth rates are assuredly very high but are in fact within the range of feasibility if the methods of intense forest management were universally applied (see Table 13). Ballard (1984, p. 353) writes "There appears to be an opportunity to increase the productivity of the world's major coniferous 'wood baskets' by at least 50 percent by intensive fertilization." We would have to do better than that. If the wood had to be harvested and stored, that would amount to 19.2 x 10^9 m^3 of wood annually, over 6 times the 1983 global wood harvest.

What these figures show is that it is physically possible to remove 5 x 10^9 tons C yr^{-1} from the atmosphere either in new forests, in intensively managed forests on existing forest land, or in some combination that one might choose to elaborate. As Dyson and Marland concluded in 1979, there is no physical law that says our target cannot be achieved.

Financial and political limits are additional factors. We have not considered here the dollar and energy costs of fertilizer and forest management. Dyson and Marland (1979) recognized that these

TABLE 16. INCREASE IN FOREST AREA AND/OR PRODUCTIVITY REQUIRED IN ORDER TO REMOVE AN ADDITIONAL 5 x 10^9 TONS OF CARBON PER YEAR FROM THE ATMOSPHERE

Scheme	Area (10^6 ha)	Yield Increase Required (m^3 ha^{-1} yr^{-1})	Yield Increase Required Tons C (ha^{-1} yr^{-1})
New plantations equivalent to American sycamore on short rotation in Georgia (Dyson and Marland, 1979)	670		7.5
New plantations equivalent to current tropical plantations (Upper limit from Brown et al., 1986)	520	37	9.6
Uniform increase in all closed forests	2937	6.5	1.70
Uniform increase in closed tropical forests	1201	16.0	4.16
1/3 of C in closed temperate forest	1736	3.7	0.96
2/3 of C in closed tropical forest	1201	10.7	2.78
Each country takes care of its own CO_2 in its own closed forests (1982 CO_2 production rates)	USSR	4.4	1.1
	USA	22.4	5.8
	China	12.7	3.3
	India	5.5	1.4
	Mexico	5.9	1.5
	Brazil	0.4	0.1
	Canada	1.6	0.4
	Indonesia	0.7	0.2
	Japan	36.4	9.5
	Zaire	0.04	0.01
	West Germany	99.5	25.9

would be major factors in forestry at this scale. Neither have we discussed the ecological consequences of such a project or the practicality of storing a large quantity of harvested wood, much of it perhaps in useful, long-lived products. Our discussion of the political aspects of such a project has been a list of major obstacles.

Recall, however, that what we are contemplating is a relatively short-term response to a perception of severe ecological impact of long-term climate change. The challenge for future studies is to compare the economic, political, and ecological costs of reforestation to the costs of suddenly rejecting the use of fossil fuels or of accommodating to major climatic change. Ultimately if we are to increase the net annual increment of forest growth it will be to meet some need for wood. It will be because either the value of wood has increased or its cost has decreased; and part of that equation will be the cost of major changes in global climate.

Mathews (1987) has concluded that the U.S. should act now to avoid any unacceptably large greenhouse warming. She believes that "because of the scientific uncertainties, any preventive measure should be either inexpensive, given the context, or economically justifiable on its own merits" (Mathews, 1987, p. 66). She argues that there are measures that make economic sense and seem politically realistic. Foremost among these options are efforts toward energy efficiency and reduced reliance on carbon-based fuels but "slowing or reversing deforestation may also help" (Mathews, 1987, p. 59). She urges that the costs of waiting for scientific certainty are too large, that we need to act now.

Trabalka et al. (1985, p. 266-267) conclude that "large-scale reforestation is not a realistic option for mitigation if one considers the most probable estimates of further CO_2 increase" and "concepts of a large net biospheric carbon sink over the next century fly in the face of realities that include a projected minimum doubling of human population in tropical regions." This conclusion was based in large measure on the observation we have shared, that forests managed for maximum production contain less carbon that those managed for maximum biomass. They saw an incompatibility between reforestation to limit atmospheric CO_2 and increases in wood production, especially for energy. This is true enough unless we are prepared to either use or store wood in such a way that the carbon is not oxidized or unless we can replace fossil fuel consumption with wood consumption.

In their initial analysis of using forests to take up excess CO_2, Dyson and Marland (1979) ended by concluding that although the scheme was massive in scale and raised the question of feasibility, there was no law of nature to prohibit its success. They suggested the biologically-based schemes for collecting CO_2 had the greatest possibility of being used. This additional analysis supports those conclusions but focuses attention on increasing the productivity of existing forest area rather than trying to significantly increase forest area. The dimensions of the "fix" are staggering! It does not now meet Mathews (1987) requirement of "economically justifiable on its own merits." This analysis suggests that although looking to forests to solve the CO_2 problem is unrealistic, reforestation could indeed play a significant role as one component among a variety of measures taken to address increasing CO_2.

This analysis also supports the conclusion of Salati and Vose (1983) that the most important requirement with respect to tropical forests now, may be buying time, minimizing the loss of choice.

ACKNOWLEDGEMENTS

This research was sponsored by the Carbon Dioxide Research Division, Office of Energy Research, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. The paper has profited immensely from comments by and discussion with Jack Ranney. Comments from Bob Cushman, R. A. Houghton, and Sandra Brown have been helpful in refining the ideas and presentation. Publication No. 3058, Environmental Sciences Division, ORNL.

REFERENCES

Albanese, A.S. and M. Steinberg.1980. "Environmental Control Technology for Atmospheric Carbon Dioxide," Final Report, U.S. Department of Energy, DOE/EV-0079, 51 pp.

Armentano, T.V.1984. "Effects of Increased Wood Energy Consumption on the Carbon Storage in Forests of the United States," Environmental Management 8:529-538.

Armentano, T.V. and C.W. Ralston. 1980. "The Role of Temperate Zone Forests in the Global Carbon Cycle," Canadian Journal of Forest Research 10:53-60.

Armentano, T.V. and J. Hett (eds). 1980. "The Role of Temperate Zone Forests in the World Carbon Cycle. Problem Definition and Research Needs," U.S. Department of Energy, CONF-7903105.

Armentano, T.V. and E.S. Menges. 1986. "Patterns of Change in the Carbon Balance of Organic Soil-Wetlands of the Temperate Zone," Journal of Ecology 74:755-774.

Baes, C.F., Jr., S.E. Beall, D.W. Lee, and G. Marland. 1980. "The Collection, Disposal, and Storage of Carbon Dioxide," in W. Bach, J. Pankrath, and J. Williams (eds.), Interactions of Energy and Climate. (Boston: Reidel Publishing Company), pp. 495-519.

Baes, C.F., Jr., A. Björkström, and P.J. Mulholland. 1985. "Uptake of Carbon Dioxide by the Oceans," in J.R. Trabalka (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle, U.S. Department of Energy, DOE/ER-0239, December 1985, pp. 81-112.

Ballard, R. 1984. "Fertilization of Plantations," in G.D. Bowen and E.K.S. Nambiar (eds.), Nutrition in Plantation Forests (London, Academic Press), pp. 327-360.

Barr, T.N. 1981. "The World Food Situation and Global Grain Prospects," Science 214:1087-1095.

Bevege, D.I. 1984. "Wood Yield and Quality in Relation to Tree Nutrition," in G.D. Bowen and E.K.S. Nambiar (eds.), Nutrition of Plantation Forests (London: Academic Press), pp. 293-326.

Binkley, D., 1986, Forest Nutrition Management, J. Wiley and Sons, New York.

Borough, C.J., W.D. Incoll, J.R. May, and T. Bird. 1984. "Chapter 10: Yield Statistics," in W.E. Hillis and A.G. Brown (eds.), Eucalypts for Wood Production (New York: Academic Press), pp. 201-225.

Bowen, G.D. and E.K.S. Nambiar. 1984. "Future Directions in Plantation Nutrition Research," in G.D. Bowen and E.K.S. Nambiar (eds.), Nutrition in Plantation Forests (London: Academic Press), pp. 489-506.

Brown, C.L. 1976. "Forests as Energy Resources in the Year 2000: What Man Can Imagine, Man Can Do," Journal of Forestry vol. 74, January 1976, 6 pp.

Brown, S. 1980. "Rates of Organic Matter Accumulation and Litter Production in Tropical Forest Ecosystems," in S. Brown, A.E. Lugo, and B. Liegel (eds.), The Role of Tropical Forestation on the World Carbon Cycle, U.S. Department of Energy, CONF-800350, August.

Brown, S. and A.E. Lugo. 1982. "The Storage and Production of Organic Matter in Tropical Forests and Their Role in the Global Carbon Cycle," Biotropica 14:161-187.

Brown, S. and A.E. Lugo. 1984. "Biomass of Tropical Forests: A New Estimate Based on Volumes," Science 223:1290-1293.

Brown, L.R. and E.C. Wolfe. 1985. "Reversing Africa's Decline," Worldwatch Paper 65 (Washington, D.C.: The Worldwatch Institute), 81 pp.

Brown, S., A.E. Lugo, and J. Chapman. 1986. "Biomass of Tropical Tree Plantations and Its Implications for the Global Carbon Budget," Canadian Journal of Forest Research 16:390-394.

Clawson, M. 1979. "Forests in the Long Sweep of American History," Science 204:1168-1174.

Cooper, C.F. 1983. "Carbon Storage in Managed Forests," Canadian Journal of Forest Research 13:155-166.

Cropper, W.P., Jr., and K.C. Ewel. 1987. "A Regional Carbon Storage Simulation for Large-Scale Biomass Plantations." Ecological Modelling 36:171-180.

Delcourt, H.R. and W.F. Harris. 1980. "Carbon Budget of the Southeastern U.S. Biota: Analysis of Historical Change in Trend from Source to Sink," Science 210:321-323.

Detwiler, R.P., C.A.S. Hall, and P. Bogdonoff. 1985. "Land Use Change and Carbon Exchange in the Tropics-11. Estimates for the Entire Region," Environmental Management 9:335-344.

Dyson, F.J. 1976. "Can We Control the Amount of Carbon Dioxide in the Atmosphere," IEA(O)-76-4, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, July, 13 pp.

Dyson, F.J. and G. Marland. 1979. "Technical Fixes for the Climatic Effects of CO2," in W.P. Elliott and L. Machta (eds.), Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels, Miami Beach, Florida, March 7-11, 1977, U.S. Department of Energy, CONF-770385, pp. 111-118.

FAO. 1976. Forest Resources in the European Region, Food and Agriculture Organization of the United Nations, Rome.

FAO. 1981. "Tropical Forest Resources Assessment Project: Forest Resources of Tropical America, Forest Resources of Tropical Africa, Forest Resources of Tropical Asia," Food and Agriculture Organization of the United Nations, Technical Reports Nos. 1, 2, and 3, U.N. 32/6:1301-78-04, Rome.

FAO. 1982. "Conservation and Development of Tropical Forest Resources," FAO Forestry Paper 37, Food and Agriculture Organization of the United Nations, Rome.

FAO. Forestry Department. 1985a. "Forestry Beyond 2000," Unasylva 37:7-16.

FAO. 1985b. "Intensive Multiple-Use Forest Management in the Tropics," FAO Forestry Paper 55, Food and Agriculture Organization of the United Nations, Rome.

Farnum, P., R. Timmis, J.L. Kulp. 1983. "Biotechnology of Forest Yield," Science 219:694-702.

Fearnside, P.M. 1986. "Spatial Concentration of Deforestration in the Brazilian Amazon," Ambio 15:74-81.

Ford, E.D. 1984. "The Dynamics of Plantation Growth," in G.D. Bowen and E.K.S. Nambiar (eds.), Nutrition in Plantation Forests (London: Academic Press), pp. 17-52.

Fraser, M.D., J.F. Henry, C.W. Vail. 1976. "Design, Operation and Economics of the Energy Plantation," Proceedings of Symposium, Clean Fuels from Biomass, Sewage, Urban Refuse, Agricultural Waste (Chicago: Institute of Gas Technology), pp. 371-395.

Gates, D.M. 1985. "Global Biospheric Response to Increasing Atmospheric Carbon Dioxide Concentration," in B.R. Strain and J.D. Cure (eds.), Direct Effects of Increasing Carbon Dioxide on Vegetation, U.S. Department of Energy DOE/ER-00238, December, pp. 171-186.

Gerhold, H.D., R.E. Goddard, G.I. McDonald. 1986. "Breeding Out Disease," Journal of Forestry, vol. 84, no. 2, pp. 49-53.

Goddard, R.E. and C.A. Hollis. 1984. "The Genetic Basis of Forest Tree Nutrition," in G.D. Bowen and E.K.S. Nambiar (eds.), Nutrition in Plantation Forests (London: Academic Press), pp. 237-258.

Hansen, E.A. 1987. "Research Strategy for Attaining High Yielding Populus Energy Plantations." in D.L. Klass (ed.), Energy and Biomass From Wastes X. pp. 121-131. Elsevier Applied Science Publishers, London.

Heilman, P.E., and R. F. Stettler. 1985. "Genetic Variation and Productivity of Populus Trichocarpa T and G and its Hybrids. II. Biomass Production in a 4-year Plantation." Canadian Journal of Forest Research 15:384-388.

Hilbert, D. W., T. I. Prudhomme, and W.C. Oechel. 1987. "Response of Tussock Tundra to Elevated Carbon Dioxide Regimes: Analysis of Ecosystem CO_2 Flux Through Nonlinear Modeling." Oecologia 72:466-472.

Holowacz, J. 1985. "Forests of the U.S.S.R.," The Forestry Chronicle, vol. 61, no. 5, October, pp. 366-373.

Houghton, R.A. 1986. "Estimating Changes in the Carbon Content of Terrestrial Ecosystems from Historical Data," in J.R. Trabalka and D.E. Reichle (eds.), The Changing Carbon Cycle: A Global Analysis, (New York: Springer-Verlag), pp. 175-193.

Houghton, R.A., J.E. Hobbie, J.M. Melillo, B. Moore, B.J. Peterson, G.R.Shaver, and G.M. Woodwell. 1983. "Changes in the Carbon Content of Terrestrial Biota and Soils Between 1860 and 1980: A Net Release of CO2 to the Atmosphere," Ecological Monographs 53:235-262.

Houghton, R.A., W.H. Schlesinger, S. Brown, and J.F. Richards. 1985a. "Carbon Dioxide Exchange Between the Atmosphere and Terrestrial Ecosystems," in J.R. Trabalka (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle, U.S. Department of Energy, DOE/ER-0239, pp. 113-140.

Houghton, R.A., R.D. Boone, J.M. Melillo, C.A. Palm, G.M. Woodwell, N. Myers, B. Moore III, and D.L. Skole. 1985b. "Net Flux of Carbon Dioxide from Tropical Forests in 1980," Nature 316:617- 620.

Houghton, R.A., R.D. Boone, J.R. Fruci, J.E. Hobbie, J.M. Melillo, C.A. Palm, B.J. Peterson, G.R. Shaver, G.M. Woodwell, B. Moore, D.L. Skole, and N. Myers. 1987. "The Flux of Carbon From Terrestrial Ecosystems to the Atmosphere in 1980 due to Changes in Land Uses: Geographic Distribution of the Global Flux." Tellus 39B:122-129.

Hyde, W.F., and F.J. Wells. 1979. "The potential energy productivity of U.S. Forests," Energy Sources 4:231-257.

Johnson, W.C., and D.M. Sharpe. 1983. "The Ratio of Total to Merchantable Forest Biomass and the Application to the Global Carbon Budget," Canadian Journal of Forest Research 13:372-383.

Jordan, C.F. (ed.). 1986. Amazonian Rain Forests: Ecosystem Disturbance and Recovery. Ecological Studies 60. Springer-Verlag, New York.

Kimball, B.A. 1985. "Adaptation of Vegetation and Management Practices to a Higher Carbon Dioxide World," in B.R. Strain and J.D. Cure (eds.), Direct Effects of Increasing Carbon Dioxide on Vegetation, U.S. Department of Energy, DOE/ER-00238, December.

LaMarche, V.C., Jr., D.A. Graybill, H.C. Fritts, and M.R. Rose. 1984. "Increasing Atmospheric Carbon Dioxide: Tree Ring Evidence for Growth Enhancement in Natural Vegetation," Science 225:1019- 1021.

Lanly, J.P. 1982. "Tropical Forest Resources," Forestry Paper 30, Food and Agriculture Organization of the United Nations, Rome.

Los Alamos National Laboratory. 1987. "Reforestation is Draining the Water Supply." Los Alamos National Laboratory Newsletter, vol. 7, no. 31, August 14, 1987.

Lugo, A.E., and S. Brown. 1986. "Steady State Terrestrial Ecosystems and the Global Carbon Cycle." Vegetatio 68:83-90.

Marchetti, C. 1976. "On Geoengineering and the CO2 Problem," Research Memorandum RM-76-17, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Marks, P.L., and F.H. Bormann. 1972. "Revegetation Following Forest Cutting: Mechanisms for Return to Steady-State Nutrient Cycling," Science 176:914-915.

Marland, G. 1987. "Technical Fixes for Limiting the Increase of Atmospheric CO_2: A Review," (in press).

Mathews, J.T. 1987. "Global Climate Change: Toward a Greenhouse Policy," Issues in Science and Technology, Spring, pp. 57-68.

Matthews, E. 1983. "Global Vegetation and Land Use: New High-Resolution Data Base for Climate Studies," Journal of Climate and Applied Meteorology 22:474-487.

Merrick, T.W. 1986. "Population Pressures in Latin America," Population Bulletin, vol. 41, no. 3, (Washington, D.C.: Population Reference Bureau, Inc.), July, 50 pp.

Molofsky, J., C.A.S. Hall, and N. Myers. 1986. "A Comparison of Tropical Forest Surveys," U.S. Department of Energy, DOE/NBB-0078, June.

de Montalembert, M.R. and J. Clement. 1983. "Fuelwood Supplies in the Developing Countries," Forestry Paper 42, Food and Agriculture Organization of the United Nations, Rome.

Myers, N. 1976. "An Expanded Approach to the Problem of Disappearing Species," Science 193:198-202.

Myers, N. 1980. "Conversion of Tropical Moist Forests," (Washington, D.C.: National Academy of Sciences), 205 pp.

Nambiar, E.K.S. 1984. "Plantation Forests: Their Scope and a Perspective on Plantation Nutrition," in G.D. Bowen and E.K.S. Nambiar (eds.), Nutrition of Plantation Forests (London: Academic Press), pp. 1-15.

Namkoong, G. 1986. "Genetics and the Forests of the Future," Unasylva 38:2-18.

Oechel, W.C. and B.R. Strain. 1985. "Native Species Responses to Increased Atmospheric Carbon Dioxide Concentration," in B.R. Strain and J.D. Cure (eds.), Direct Effects of Increasing Carbon Dioxide on Vegetation, U.S. Department of Energy, DOE/ER-00238, December, pp. 117-154.

Olson, J.S. and J.A. Watts. 1982. "Carbon in Land Vegetation," in W.C. Clark (ed.), Carbon Dioxide Review: 1982 (New York: Oxford University Press), pp. 435-438.

Olson, J.S., R.M. Garrels, R.A. Berner, T.V. Armentano, M.I. Dyer, and D.H. Yaalon. 1985. "The Natural Carbon Cycle," in J.R. Trabalka (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle, U.S. Department of Energy, DOE/ER-0239, pp. 175-214.

Pearse, P.H., A.J. Lang, and K.L. Todd. 1986. "The Backlog of Unstocked Forest Land in British Columbia and the Impact of Reforestation Programs," Forestry Chronicle 62(6):514-521.

Peterson, B.J. and J.M. Melillo. 1985. "The Potential Storage of Carbon Caused by Eutrophication of the Biosphere," Tellus 37B:117-127.

Postel, S. 1984. "Air Pollution, Acid Rain, and the Future of Forests," Worldwatch Paper 58 (Washington, D.C.: Worldwatch Institute).

Ranney, J.W., L.L. Wright, and P.A. Layton. 1987. "Hardwood Energy Crops: The Technology of Intensive Culture." Journal of Forestry, 17-28.

Richards, J.F., E.S. Haynes, J.R. Hagen, E.P. Flint, J. Arlinghaus, J.B. Dillon, and A.L. Reber. 1987. "Changing Land Use in Pakistan, Northern India, Bangladesh, Burma, Malaysia, and Brunei, 1880-1980," U.S. Department of Energy Report (in press).

Rotty, R.M. 1986. "Estimates of CO2 from Wood Fuel Based on Forest Harvest Data," Climatic Change 9:311-326.

Salati, E. and P.B. Vose. 1983. "Depletion of Tropical Rain Forests," Ambio 12:67-71.

SCEP. 1970. "Mans Impact on the Global Environment: Assessment and Recommendation for Action, Report of the Study of Critical Environmental Problems," (Cambridge, MA: MIT Press).

Schooley, F.A. S.J. Mava, D.A. Mendel, P.C. Meagher, and E.C. So. 1979. "Water and Land Availability for Energy Farming," U.S Department of Energy, DOE/ET/20076-T1.

Sheffield, R.M. and N.D. Cost. 1987. "Behind the Decline," Journal of Forestry, vol. 85, no. 1, pp. 29-33.

Shiva, V., J. Bandyopadhyay and N.D. Jayal. 1985. "Afforestation in India: Problems and Strategies," Ambio 14:329-333.

Siegenthaler, U. and H. Oeschger. 1987. "Biospheric CO_2 emissions during the past 200 years reconstructed by deconvolution of ice core data," Tellus 39B:140-154.

Smil, V. 1983. "Deforestation in China," Ambio 12:226-231.

Smith, S.V. 1981. "Marine Macrophytes as a Global Carbon Sink," Science 211:838-840.

Solomon, A.M., M.L. Tharp, D.C. West, G.E. Taylor, J.W. Webb, and J.L. Trimble. 1984. "Response of Unmanaged Forests to CO2-Induced Climate Change: Available Information, Initial Tests, and Data Requirements," U.S. Department of Energy, DOE/NBB-0053.

Steinbeck, K. and C.L. Brown. 1976. "Yield and Utilization of Hardwood Fiber Grown on Short Rotations," in Applied Polymer Symposium No. 28, (New York: J. Wiley and Sons), pp. 393-401.

Stoddard, C.H. and G.M. Stoddard. 1987. Essentials of Forestry Practice, 4th Edition (New York: J. Wiley and Sons).

Strain, B.R. and T.V. Armentano. 1982. "Response of 'Unmanaged' Ecosystems," vol. II, Part 12 of Environmental and Societal Consequences of a Possible CO2-induced Climate Change, U.S. Department of Energy, DOE/EV/10019-12.

Strain, B.R. and J.D. Cure (eds.). 1985. Direct Effects of Increasing Carbon Dioxide on Vegetation, U.S. Department of Energy, DOE/ER-0238.

Trabalka, J.R., J.A. Edmonds, J.M. Reilly, R.H. Gardner, and L.D. Voorhees. 1985. "Human Alterations of the Global Carbon Cycle and the Projected Future," in J.R. Trabalka (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle, U.S. Department of Energy, DOE/ER-0239, pp. 247-288.

Turnbull, J.W. and L.D. Pryor. 1984. "Choice of Species and Seed Sources," Chapter 2, in W.E. Hillis and A.G. Brown (eds.), Eucalypts For Wood Production (New York: Academic Press), pp. 6-65.

U.S. Forest Service, Department of Agriculture. 1982. "An Analysis of the Timber Situation in the United States, 1952-2030," Forest Resource Report No. 23, December.

U.S. Interagency Task Force on Tropical Forests. 1980. "The World Tropical Forests: A Policy, Strategy, and Program for the United States," Report to the President, U.S. Department of State Publication 9117, May.

van den Driessche, R. 1984. "Nutrient Storage, Retranslocation and Relationship of Stress to Nutrition," in G.D. Bowen and E.K.S. Nambiar (eds.), Nutrition of Plantation Forests (London: Academic Press), pp. 181-210.
Vidyasagar, T.R. 1986. "Greenhouse Cure," Nature 323:390.
Vietmeyer, N.D. 1986. "Lesser-Known Plants of Potential Use in Agriculture and Forestry," Science 232:1379-1384.
Wigley, T.M.L., K.R. Briffa, and P.D. Jones. 1984. "Atmospheric Carbon Dioxide: Predicting Plant Productivity and Water Resources," Nature 312:102-103.
Wilson, A.T. 1978. "Pioneer Agriculture Explosion and CO2 Levels in the Atmosphere," Nature 273:40-41.
World Resources Institute and the International Institute for Environment and Development. 1986. World Resources 1986, J.T. Mathews, project director (New York: Basic Books, Inc.).
Zavitkovski, J., and J.G. Isebrands. 1983. "Biomass Production and Energy Accumulation in the World's Forests." The Seventh International FPRS Industrial Wood Energy Forum '83 1:12-22. Forest Products Research Society, Madison, Wisconsin.

A GREEN FIX TO THE GLOBAL WARM-UP

Planting Trees—Lots of Them—Can Remove a Good Portion of the Carbon That Is Pushing Temperatures Up.

BY SANDRA POSTEL

Of the twists and turns in the evolutionary path that have led to life on earth as we know it, no more important a juncture can be retraced than the emergence of green plants nearly two billion years ago. Their ability to capture sunlight and use it to make food from simple chemical compounds—the process called photosynthesis—dramatically altered the composition of the atmosphere. It released pure oxygen into a world that had evolved without it, a happening British scientist James E. Lovelock has called "the worst atmospheric pollution incident that this planet has ever known."

The change was gradual—lethal, too, for many organisms of the time—and eventually allowed for an explosion of oxygen-breathing life forms—from the early fish and amphibians, through the dinosaurs and prehistoric mammals, to humans.

This ancient tale contains an important lesson for today. Earthly life and the atmosphere that envelops it feed and shape each other. They coexist in a precarious balance that once upset can have profound and irreversible consequences.

Over the last century—a mere instant of geologic time—the activities of the human species have caused unprecedented changes in the atmosphere. A continuing buildup of certain chemical compounds—most importantly, carbon dioxide—is propelling the environment toward another potentially catastrophic shift. The earth's climate may change more during our children's lives than it has in the last 15,000 years.

While some climatic change is already inevitable, societies can gain precious time to adapt if action is taken now to dampen its ultimate magnitude and slow its pace. The first step requires curbing the use of coal, oil and natural gas, now the leading cause of the carbon dioxide buildup.

But there is another step crucial to restoring atmospheric balance: protecting our remaining forests and planting more trees. Forests and woodlands are vast storehouses of carbon, so clearing and burning them—as is now happening on a large scale in the tropics—contributes to carbon dioxide-induced climate change. Because trees remove carbon dioxide from the air through photosynthesis, planting more of them can be part of the remedy. Therein lies an opportunity to capitalize on that enduring link between earthly life and the atmosphere—by reforesting the earth.

A Cycle Out of Sync

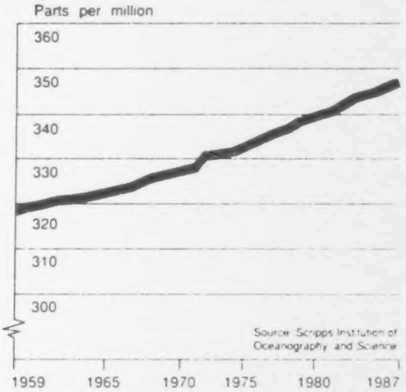
Carbon dioxide, or CO_2, makes up just .03 percent of the atmosphere's volume, a minuscule amount compared with the 78 percent share for nitrogen and 21 percent for oxygen. Yet it serves a function essential to the earth's habitability. Like a one-way filter, CO_2 lets energy from the sun pass through it but traps the longer wavelength radiation emitted back from the earth's surface.

This phenomenon, dubbed "the greenhouse effect," helps regulate the planet's temperature. Without it, the earth would be covered with ice.

Besides the atmospheric pool of CO_2, carbon is stored on land in living, dead and fossilized organic matter, and in great quantities in the oceans. Carbon naturally flows between the land, air and sea through vari ous biological and chemical processes, but its distribution between these reservoirs is now changing in a major way.

Since the middle of the last century, human activities have markedly accelerated the transfer of carbon from the land to the atmosphere. Fossil fuel combustion has spewed 150 to 190 billion tons of carbon into the air, and forest clearing for cropland and fuelwood has contributed an additional 90 to 180 billion tons.

Figure 1. Atmospheric Concentration of Carbon Dioxide, 1959-87.



Source: Scripps Institution of Oceanography and Science

Although the oceans have absorbed some of this excess, the atmospheric CO_2 level has continued to creep upward. From 280 parts per million prior to 1860, it had climbed to 348 parts per million by 1987, an increase of about one-fourth (see Figure 1). Just since 1958, when scientists began routinely to monitor the CO_2 concentration, it has risen 10 percent.

The Climatic Consequences

Scientists usually use a doubling of CO_2 over preindustrial levels as a benchmark for examining what climatic changes the buildup will bring. Their models show that such a doubling, to be reached sometime after the middle of the next century, would cause the earth's average temperature to increase by 3 to 9 degrees Fahrenheit. Though a change of that magnitude may seem trivial, it helps to note that the average temperature during the last Ice Age—when vast sheets of ice covered much of Europe and North America—was only about 9 degrees colder than it is today. Moreover, because the concentrations of several other greenhouse gases also are increasing, the *equivalent* of this doubling may occur within 50 years.

As the earth warms, temperature and rainfall patterns will shift. Some key food producing regions—including the North American breadbasket—could become more vulnerable to heat waves, drought and the loss of irrigation water.

Some regions, on the other hand, will benefit from the change. In Canada, northern Europe and the Soviet Union, agricultural production might expand northward with the higher temperatures and milder winters. Warmer and wetter conditions in India and parts of southeast Asia could allow rice production to increase.

But no matter how winners and losers shake out in the long run, the costs of adjusting to a changed climate will be enormous. Worldwide expenditures on newly needed irrigation and drainage systems alone could total $200 billion. Demand for new crop varieties and production methods better matched to the changed temperature and rainfall conditions will add greatly to adjustment costs.

Expensive as agricultural changes will be, ultimately the highest price tag may hang on a rise in sea level as the oceans expand and as parts of glaciers and polar ice caps melt. Officials will have to decide whether to invest huge sums in dikes and other structures to hold back the sea from such populous coastal cities as New Orleans and Shanghai, or to relocate millions of people. Contemplating the prospect of sea-level rise, President Maumoon Abdul Gayoom of the Maldives has called his cluster of 1,196 low-lying islands off the southwest coast of India "an endangered nation."

Recent findings suggest that the greenhouse warming, long an intriguing hypothesis, may have already begun. In late June, James E. Hansen, head of the National Aeronautics and Space Administration's Goddard Institute for Space Studies, publicly released findings from a study of global temperature records spanning the last century. The key conclusions, as Hansen presented in written testimony to a U.S. Senate committee, were that "present global temperatures are the highest in the period of instrumental records . . . The rate of global warming in the past two decades is higher than at any earlier time in the record." And perhaps most alarming, "the four warmest years in the past century all have occurred in the eighties," and "the first five months of 1988 are so warm globally that we conclude [this year] will be the warmest . . . on record unless there is a remarkable, improbable cooling."

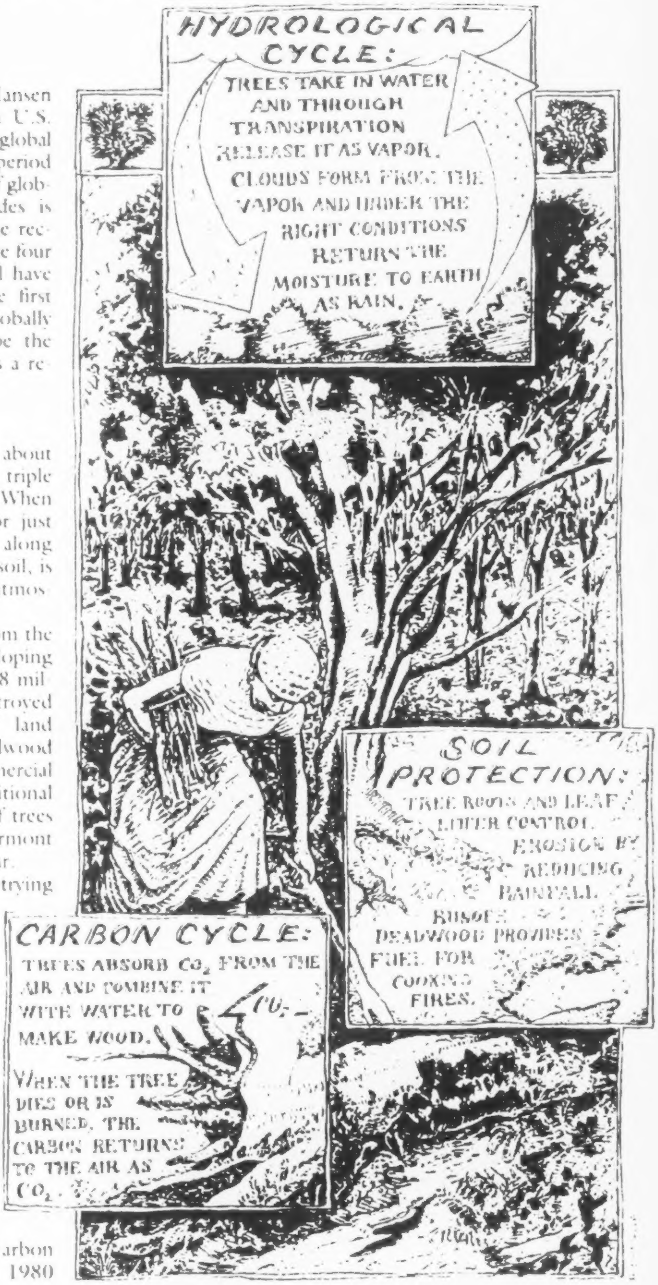
Taking Stock of the Forests

The earth's trees, shrubs and soils hold about two trillion tons of carbon, roughly triple the amount stored in the atmosphere. When vegetation is cleared and burned, or just left to decay, the carbon it contains, along with some of that in the underlying soil, is oxidized and released to join the atmospheric pool of carbon dioxide.

Today the bulk of CO_2 emitted from the land in this way comes from developing countries in the tropics. Each year, 28 million acres of tropical forest are destroyed through the combined action of land clearing for crop production, fuelwood gathering and cattle ranching. Commercial timber harvesting degrades an additional 11 million acres. All told, an area of trees slightly larger than New York and Vermont combined is lost or logged each year.

Scientists have spent many years trying to pinpoint how much carbon is added to the atmosphere through forest clearing. Their estimates are clouded by large uncertainty about the rates of deforestation in different regions, the extent of forest regrowth after clearing, the amount of carbon actually contained in the lands being cleared, and how quickly that carbon makes its way into the atmosphere.

Over the last decade, the range among these estimates has narrowed. In a January 1988 *Science* magazine article, R.P. Detwiler and Charles Hall placed the amount of carbon released by tropical deforestation in 1980


HYDROLOGICAL CYCLE:
TREES TAKE IN WATER AND THROUGH TRANSPIRATION RELEASE IT AS VAPOR. CLOUDS FORM FROM THE VAPOR AND UNDER THE RIGHT CONDITIONS RETURN THE MOISTURE TO EARTH AS RAIN.
SOIL PROTECTION:
TREE ROOTS AND LEAF LITTER CONTROL EROSION BY REDUCING RAINFALL RUNOFF. DEADWOOD PROVIDES FUEL FOR COOKING FIRES.
CARBON CYCLE:
TREES ABSORB CO_2 FROM THE AIR AND COMBINE IT WITH WATER TO MAKE WOOD.
CO_2
WHEN THE TREE DIES OR IS BURNED, THE CARBON RETURNS TO THE AIR AS CO_2.

somewhere between 0.4 and 1.6 billion tons.[4] Another authoritative study, led by Richard Houghton, associate scientist at the Woods Hole Research Institute in Massachusetts, figured it to be between 0.9 and 2.5 billion tons. Since about 5 billion tons are emitted each year by fossil fuel burning, the midpoint of Houghton's estimate would attribute one quarter of the total annual carbon buildup to deforestation.

Table 1.

Estimated Net Release of Carbon to the Atmosphere from Tropical Deforestation, Leading Countries, 1980

Country	Net Carbon Release*	Share of Total
	(million tons)	(percent)
Brazil	336	20
Indonesia	192	12
Colombia	123	7
Ivory Coast	101	6
Thailand	95	6
Subtotal	**847**	**51**
Others	812	49
Total	**1,659**	**100**

* Figures are midpoints of estimated ranges.
Source: R.A. Houghton et al., "The Flux of Carbon from Terrestrial Ecosystems to the Atmosphere in 1980 Due to Changes in Land Use: Geographic Distribution of the Global Flux," Tellus, February/April 1987.

Houghton and his colleagues have also painted an interesting picture of the geographic distribution of these carbon emissions. They estimate 40 percent comes from tropical America, 37 percent from tropical Asia, and 23 percent from tropical Africa. Just five countries account for half of all carbon emissions: Brazil, Colombia, Indonesia, the Ivory Coast and Thailand (see Table 1).

Brazil alone already contributes a fifth of the total, a figure likely to rise with the accelerating deforestation in parts of the Amazon. Indeed, a recent study of satellite data by Brazil's Institute of Space Research suggests that 20 million acres of forest were cleared and burned in the Brazilian Amazon in 1987, releasing 500 million tons of carbon into the atmosphere, a figure nearly 50 percent greater than the mid-point of Houghton's estimate of 336 million tons.

An Element of Surprise

A worrisome twist to the forest-climate change link is how the world's remaining forests will behave in a warmer climate and an atmosphere richer in CO_2. That response could actually exert an even greater influence on the earth's climate than does deforestation.

Trees, like other green plants, grow through the process of photosynthesis. They take carbon dioxide from the air and combine it with hydrogen from water molecules to form carbohydrates. Higher CO_2 levels usually have a fertilizing effect on plants, spurring them to grow faster. Commercial greenhouse operators, for instance, often set their CO_2 concentrations two to three times higher than the level in the natural atmosphere to boost production.

If trees did indeed grow faster as atmospheric CO_2 levels increased, they would remove carbon from the atmosphere more rapidly. This "negative feedback" would help slow the global warming. So far, unfortunately, no convincing evidence suggests that trees in their natural environments would respond this way. Other factors, such as limited nutrients and water, would in many cases prevent growth rates from increasing.

Another possibility results in positive feedback, a worsening of the warming trend. George Woodwell, director of the Woods Hole Research Institute, points out that as temperatures rise, trees and microorganisms in the soil could substantially increase their rates of respiration—the process by which cells break down carbohydrates to obtain energy, which results in a release of carbon dioxide. The increase in respiration would be greatest in the middle to higher latitudes, where the temperature rise will be most pronounced.

When respiration outpaces photosynthesis, trees release more carbon dioxide to the air than they remove from it. A graph of monthly atmospheric CO_2 levels shows this clearly: Peaks come during the northern hemisphere's autumn and winter, when the vast areas of seasonal forests release more CO_2 than they take in; valleys appear during the spring and summer, when photosynthesis is in high gear. The danger is that an increase in respiration because of rising temperatures could release more CO_2 to the atmosphere, reinforcing the very buildup that initiated the warming.

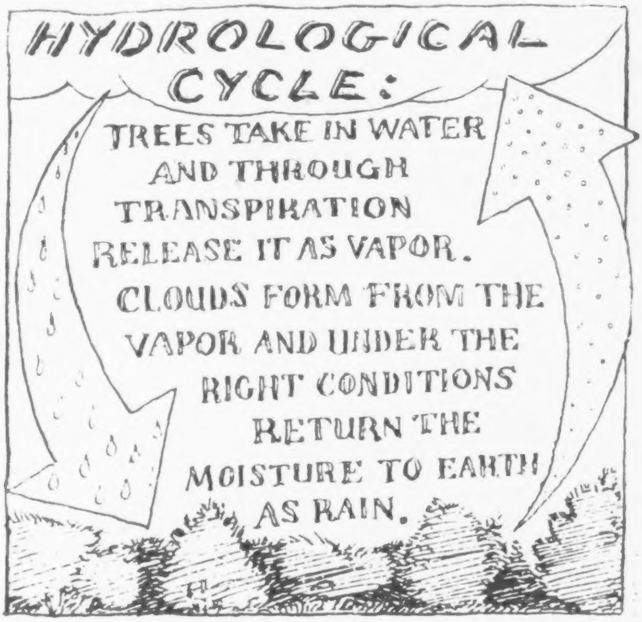
If respiration exceeded photosynthesis for an extended period of time, trees would stop growing altogether and ultimately die. New species better adapted to the altered conditions eventually would replace the old ones, but for several decades trees might die off with little replacement. Woodwell maintains that a widespread forest dieoff could release enormous amounts of carbon to the atmosphere—perhaps hundreds of billions of tons—depending on the speed of the warming. He warns that "the sudden destruction of forests by air pollution, now being experienced in northern and central Europe . . . is but a sample of the destruction that appears to be in store."

Woodwell's scenario might never come to pass. Ecologists do not yet agree on how forests will respond to a warmer climate, or even on whether that response will add CO_2 to the atmosphere or remove it. Some point out, for example, that higher temperatures would increase rates of organic decomposition, which in turn would release nutrients to the soil and thus potentially boost the productivity of trees. This could cause a helpful negative feedback: since trees would be growing faster, they would remove more CO_2 from the atmosphere, helping slow the warming.

How forests will actually respond looms large in the climate change picture, since the potential for a strong feedback—positive or negative—clearly exists.

Deforestation's Other Legacies

Protecting forests and planting trees need to be high on the international agenda for several compelling reasons other than stabilizing the global carbon cycle. The growing wave of deforestation has left in its wake a severe energy crisis in the Third World, an accelerating loss of the earth's biological diversity, and large areas of degraded land.


HYDROLOGICAL CYCLE:
TREES TAKE IN WATER AND THROUGH TRANSPIRATION RELEASE IT AS VAPOR.
CLOUDS FORM FROM THE VAPOR AND UNDER THE RIGHT CONDITIONS RETURN THE MOISTURE TO EARTH AS RAIN.

Wood provides the primary source of energy for more than two-thirds of the people in developing countries. It cooks their meals and heats their homes. As forests and woodlands shrink, fuelwood becomes increasingly hard to find for those who gather it and expensive for those who buy it.

The human costs of wood scarcity already are high. In rural parts of the Himalayas and sub-Saharan Africa, women and children spend between 100 and 300 days a year gathering fuelwood, which pulls them away from farming, education and other productive activities. The U.N. Food and Agriculture Organization projects that half the developing world could lack a sustainable supply of fuelwood by the year 2000.

Woody plants also play a vital ecological role. They secure soils, especially on steep slopes and in wind-prone regions, and help the land absorb and retain moisture by adding organic matter and structure to soils. With the loss of forest cover, the ecological integrity of many areas has disintegrated, causing land productivity to drop, droughts and floods to worsen, and rural livelihoods to become threatened.

B*ecause*
trees remove carbon dioxide
from the air through
photosynthesis, planting more
of them can be part of
the remedy to
global warming.

Finally, deforestation has driven uncounted numbers of plant and animal species to extinction by destroying their habitats. Peter Raven, director of the Missouri Botanical Garden in St. Louis and a leading expert in tropical biology, offers a rough estimate that just under half of the world's species can only be found in tropical forests that are rapidly being destroyed. As deforestation spreads, a fifth of all species could disappear during the next 15 years. "We can expect the rate of extinction to average more than 100 species a day," Raven says, "with the rate increasing from perhaps a few species a day now to several hundred by the early years of the next century. No comparable rate of extinction has occurred since the end of the Cretaceous Period, 65 million years ago," when the dinosaurs and half of all species existing at the time were wiped out.

A Living Carbon Bank

Countries are unlikely to invest substantial resources in tree planting solely to ward off global warming. But, in much of the Third World, satisfying fuelwood needs and restoring productivity to degraded ecosystems provide a sound—even urgent—rationale. Expanding forest cover for these purposes would yield the added bonus of slowing the buildup of carbon dioxide, which gives industrial countries ample reason to step up support for tree planting in the Third World.

An analysis by the Worldwatch Institute suggests that an additional 320 million acres of trees—an area nearly twice the size of Texas—will be needed by the year 2000 to meet developing countries' growing demands for fuel and industrial wood products and to rehabilitate deteriorating ecosystems. What contribution could that much tree planting make to slowing the CO_2 buildup? Too many uncertainties exist to answer this question precisely, but some back-of-the-envelope calculations suggest an important role for reforestation.

A fairly fast-growing tropical hardwood species annually yields on the order of 4 to 5.6 tons of biomass per acre. Half that weight—about 2.4 tons—is carbon that's been removed from the atmosphere through photosynthesis. Add to that some 0.2 tons of carbon that would be stored in the underlying soil, and the total annual carbon-fixing benefit of tree planting comes to 2.6 tons per acre.

Some of the trees planted for fuel would be burned in the short term and would therefore not contribute to the removal of atmospheric carbon. Still, subtracting this area from the total leaves a carbon bank of 300 million acres, which would absorb roughly 780 million tons of carbon every year until the trees reach maturity. That would cut net carbon releases from tropical forests by nearly half.

Of course, slowing the destruction of existing forests is also crucial. Halving the CO_2 contribution from deforestation in Brazil, Indonesia, Colombia and the Ivory Coast would reduce net carbon emissions from tropical forests by more than 20 percent. Together, that achievement and the carbon-storage benefits of 300 million acres of trees would cut releases from tropical forests by two-thirds. The total amount of carbon added to the atmosphere from all human activities—deforestation *and* fossil fuel combustion—would be cut by 17 percent.

Hints of Progress

According to Houghton and his colleagues, natural systems in Europe and possibly Japan and South Korea are already accumulating more carbon than they are releasing. Many European countries have in recent decades abandoned substantial areas of cropland and allowed forests to regrow. France, once 80 percent forested, had trees covering only 14 percent of its territory by the late 18th century. Today, roughly 25 percent of the country is in forest. Continued damage from air pollution and acid rain on the continent, however, could reverse this positive trend.

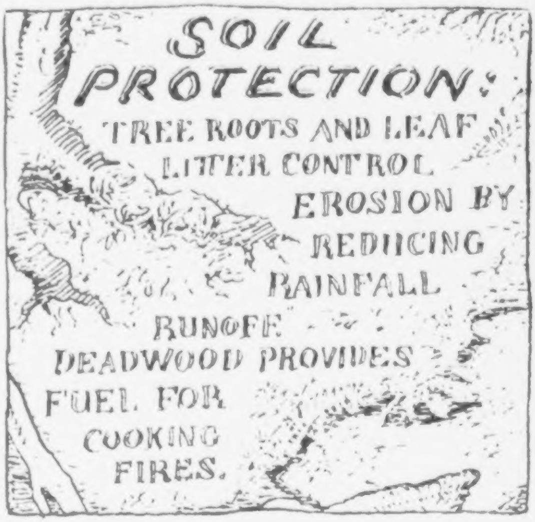
Both Japan and South Korea have purposely planted large areas in trees. Japan now has the fourth largest area of commercial tree plantations in the world, nearly 24 million acres. And in the early seventies, South Korea launched a major planting effort to reforest barren hillsides and to expand fuelwood supplies for rural villages. In less than a decade, Koreans planted an area in pines roughly equal to two thirds of the area cultivated in rice, their staple food.

As a result of the Food Security Act of 1985, the United States could also turn some of its land into a carbon bank. The act created the Conservation Reserve, under which farmers will take at least 40 million acres of highly erodible cropland out of production by 1990 and plant it in trees or grass. Each acre of recovered grassland or woodland will store roughly 16 more tons of carbon than when it was cultivated. Assuming the carbon accumulates at an average yearly rate of half a ton per acre as the land undergoes conversion, the reserve would absorb a total of 20 million tons of carbon annually for the next three decades, assuming the land remains in the reserve.

Houghton and his colleagues had estimated that U.S. and Canadian lands were adding 25 million tons of carbon to the atmosphere in 1980. So, depending on trends in forest cover and wood use, the Conservation Reserve could go a long way toward making North America's land systems a net sink for carbon.

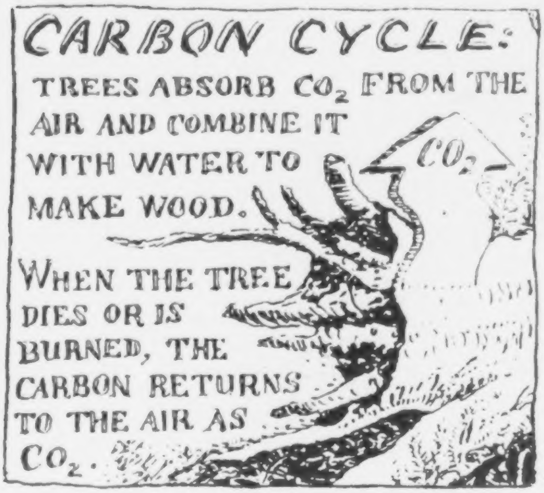
An Impossible Dream?

Here and there, people are working diligently to reforest the earth with the aim of stabilizing not the earth's climate, but their own livelihoods. Few of these rural tree planters are aware that their efforts serve the global good as well as their immediate needs—but the beauty of reforestation is that it does just that.


SOIL PROTECTION:
TREE ROOTS AND LEAF LITTER CONTROL EROSION BY REDUCING RAINFALL RUNOFF.
DEADWOOD PROVIDES FUEL FOR COOKING FIRES.

Can the community of nations plant trees on the scale required to improve prospects in the Third World and simultaneously help balance the global carbon cycle? There's reason for optimism.

International development agencies now recognize that rural people form the only labor force large enough to plant trees on the vast scale that is needed. More than ever before, this labor force is being mobilized into action. From more than a decade of experience with forestry projects, planners have learned that success lies in soliciting villagers' needs and planting trees to meet them. Choosing an appropriate species, for example, is critical. If people need fodder for their animals, a nonbrowsable species, such as eucalyptus, will not get much popular support.


CARBON CYCLE:
TREES ABSORB CO_2 FROM THE AIR AND COMBINE IT WITH WATER TO MAKE WOOD.
WHEN THE TREE DIES OR IS BURNED, THE CARBON RETURNS TO THE AIR AS CO_2.
CO_2

Not surprisingly, international relief organizations, such as CARE in the United States and Oxfam in the United Kingdom, have orchestrated some of the most successful reforestation projects to date. With strong experience at the local level, these groups can tailor planting efforts to suit specific needs. In a project aided by CARE in the Majjia Valley of Niger, for instance, trees planted to form windbreaks around cropland boosted grain yields more than 20 percent and also produced wood needed for fuel and timber.

Worldwide, thousands of women's groups, peasant collectives, churches and other small, local organizations have taken up the cause of tree planting. Among the most notable is Kenya's Greenbelt Movement, sponsored by the National Council of Women of Kenya. This group has enlisted the help of more than 15,000 farmers and a half million schoolchildren in setting up 670 community nurseries and planting more than two million trees.

Also inspiring optimism are several government leaders who in recent years have elevated reforestation to the level of national crusades. Chinese officials have set a goal of getting 20 percent of their country's territory in trees by the year 2000, up from about 12 percent at present. Although China is unlikely to meet this target, the annual planting rate did double in 1985.

Similarly, Indian Prime Minister Rajiv Ghandi tripled funding for forestry in his development agenda for 1985-90, gave forestry new prominence within his ministries, and created a National Wastelands Development Board to spearhead a "people's movement" for reforestation. The prime minister recognizes that the greatest resource for reforestation lies in the grass roots, and he has authorized the development board to distribute funds directly to schools, women's groups and other local organizations.

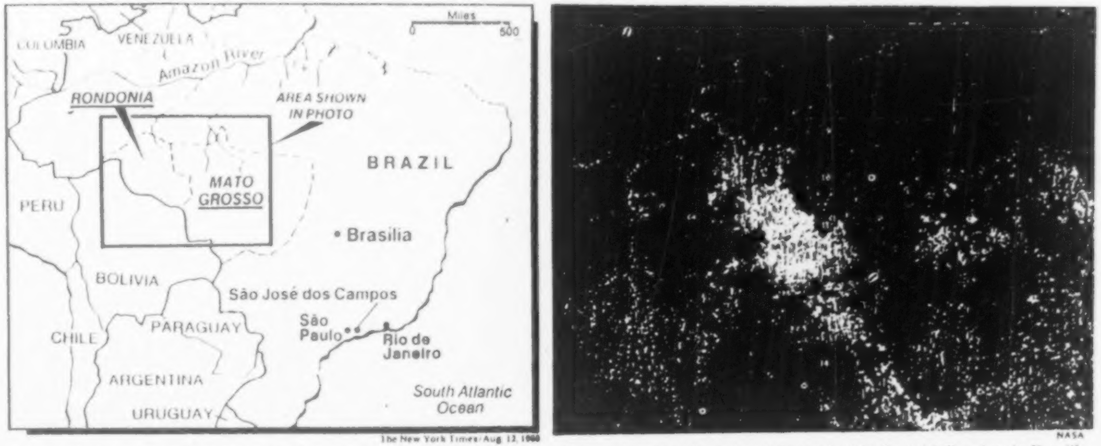
Soon to Top the Agenda

Reforestation's potential to help avert climatic change barely gets mentioned in reports or plans that sketch out forestry's future. But as the consequences of global warming become clearer, and their magnitude and cost hit home, tree planting solely for the purpose of stabilizing climate could appear on the international agenda.

Environmental philosopher Rene Dubos pleaded for people to "think globally, act locally." Perhaps no activity harmonizes global interests and local needs better than does reforestation. Reforesting an area equal to twice the size of Texas by the year 2000 entails successfully establishing some 18.4 billion trees annually. That target sounds staggering, but it would only require each person now living in the Third World to plant and care for five seedlings a year.

A strategy of forest protection and tree planting cannot by itself ward off climatic change. Since the burning of fossil fuels is currently the leading cause of the CO_2 buildup, measures to boost energy efficiency and encourage the development and use of alternative energy sources need to be in the front line of attack. But curbing deforestation and planting trees will help our generation ensure that succeeding ones inherit a habitable earth. ❑

Sandra Postel is vice president for research at Worldwatch Institute. She is co-author of the recent Worldwatch Paper "Reforesting the Earth" and of State of the World 1988.



The New York Times/Aug. 12, 1988

NASA

A composite, right, of all the satellite pictures showing forest fires in the western Amazon, mostly in the Brazilian states of Rondônia and Mato Grosso, between Aug. 1 and Sept. 18, 1987. In 1987, fires just in Brazil's part of the Amazon basin covered an estimated 77,000 square miles.

Vast Amazon Fires, Man-Made, Linked To Global Warming

By MARLISE SIMONS

Special to The New York Times

SAO JOSE DOS CAMPOS, Brazil, Aug. 6 — Like eerie ghosts of the trees and animals dying below, thick clouds of smoke are rising over the rain forest as the man-made fires of the annual dry season are once again upon the Amazon.

On some days, fires rage in thousands of places across the vast Amazon basin, following a broad belt where settlers and farmers are beating back the jungle frontier. For many, fire is the only tool for transforming forest into farm or pasture.

From the flames, tons of fumes and particles are hurled into the sky, and at night, roaring and red, the forest looks to be at war.

Now, Brazilian and American scientists in a new satellite monitoring program are for the first time pinpointing and measuring the effects of the fires. The destruction and burning of forest here is so vast, the scientists say, that it may account for at least one tenth of the global manmade output of carbon dioxide, which is believed to be causing a warming of the earth through the greenhouse effect. Burning of fossil fuels accounts for most of the carbon dioxide released worldwide.

Environmentalists have long warned of the destruction that is increasing with each new dry season, and witnesses every year report more cemeteries of trees. The scientists' findings show that in 1987 the burnings ruined more forest cover than previously thought and proved to be major polluters of the earth's atmosphere.

Continued on Page A6, Column 1

In 1987, Brazilian scientists estimate fires just in Brazil's part of the Amazon basin covered 77,000 square miles, an area one and a half times the size of New York State. Of these, at least 30,000 square miles were newly felled virgin forest, the researchers said. The remainder, they added, involved regrown forest on on previously cleared land, savannas and fields.

The pioneering studies, which include the most comprehensive estimates yet of the emissions from the Amazon fires, also found that pollution from the burnings traveled thousands of miles. This has raised questions about a possible link between the gigantic emissions from the fires in the South American tropics and the damage to the earth's protective ozone shield over Antarctica.

Smoke Rises to 12,000 Feet

Alberto Setzer, coordinator of the satellite data at the Space Research Center in this south Brazilian city, said smoke clouds from the Amazon fires often rose to 12,000 feet. Their gases and particles were then lifted up higher into jet streams and blown south across the [illegible] Atlantic, close to Antarctica. Many scientists now believe that several of these gases, including methane and nitrogen oxides, are among the reactive gases that can directly or indirectly deplete ozone, Dr. Setzer said.

© 1988 The New York Times. Reproduced by the Library of Congress, Congressional Research Service with permission of copyright claimant

New York Times
August 12, 1988

"There is no proof yet that the material is interacting with the ozone shield, which is much higher in the stratosphere," said Dr. Setzer. "But we know the material gets to the Antarctic region, and we know that storms can pump it upward. We do not know yet how high it reaches. Several people are working on this."

American scientists who took part in the mission over Antarctica by the National Aeronautics and Space Administration in October said they had not searched for or found evidence of compounds from the Amazon. But NASA researchers are now searching for such traces by satellite.

But even without the ozone question, Dr. Setzer said, the "tremendous" emissions coming off the Amazon pose serious problems. "They are large enough to cause significant changes in the chemical balance of the atmosphere and influence the global weather," he said.

A Doubly Harmful Effect

In the case of carbon dioxide, for example, the forest destruction is doubly harmful, Dr. Setzer and other researchers noted. The dwindling forest cover becomes not only less efficient in absorbing and removing this "greenhouse gas," but the fires also add new, huge volumes of it.

A report prepared by the study group at the Space Research Center estimated that the fires in Brazil last year produced carbon dioxide containing more than 500 million tons of carbon. The fires also produced 44 million tons of carbon monoxide, more than six million tons of particles, almost five million tons of methane, two and a half million tons of ozone and more than one million tons of nitrogen oxides and other substances that can circulate globally and influence radiation and climate.

"There is enough to compare it to the outburst of a very large volcano," Dr. Setzer said.

The study results on deforestation and emissions from the fires so far cover only the Brazilian two-thirds of the Amazon rain forest. Still more of the pollutants are produced by fires in parts of the Amazon basin outside Brazil.

Other Countries Studied

"Our findings in general agree with those of Brazil," said Compton Tucker, a physicist who is part of a group studying deforestation and emissions at the Goddard Space Flight Center at Greenbelt, Md. The NASA group, he said, is now also analyzing satellite data of other countries of the Amazon basin, including Bolivia and Peru, where burnings have increased.

"This phenomenon has been greatly underestimated, and until 1987 no one has ever tried to study this systematically," Dr. Tucker said. "The satellite data are also there for other areas. There are no technical constraints. They just have not been processed yet."

The effects of the fires are felt clearly on the ground in areas where the pace of destruction is greatest, including the state of Pará, in the eastern Amazon, and farther west in northern Mato Grosso and Rondônia. Here new roads have opened, and cattle and soybean farmers are felling huge areas.

Newly analyzed data for the state of Rondônia, for example, show that in 1984, when paving was completed on a highway financed by the Inter-American Development Bank, deforestation jumped from 6,500 square miles and reached 10,500 square miles in 1985. By late last year it had affected 14,600 square miles, or 17 percent of the state surface.

Respiratory Disease Rises

In August and September in past years, when the thick haze over the region worsened, it has forced airports to close down, caused boat accidents on the rivers and brought a rise in respiratory diseases.

Early this month, the annual drama of fire came to the fore as burning spread from a farm in Mato Grosso and set ablaze a national park, the Parques das Emas. The 335,000-acre park, which consists of easily flammable savannas rich in animal life, has only four wardens, who have been unable to maintain the fire corridor. The blaze lasted five days and, according to the forestry service, has destroyed 65 percent of the park.

As forestry experts explain it, spontaneous fires are rare in the moist rain forest. Rather, workers first cut the trees, leave them to dry and finally set fire to them during the dry season. Usually only the felled part is dry enough to burn, and fires remain confined to the intended areas. In the absence of transport or roads, the timber cannot be sold, and burning is the easiest way to clear the land.

In the computer room at the Space Research Center here, researchers capture and analyze the satellite images every day. Marcos Pereira, one of the analysts, explained that the satellite registers the fires as points of intense heat. These appear as dots on the screen and permit researchers to pinpoint their location. Often, the ominous dots form a belt showing the boundary between the virgin forest and the settled areas. "It is very striking how the fires follow the roads," an American researcher said.

170,000 Fires in 1987

On the worst day of 1987, Sept. 9, the satellite detected 7,603 fires. Dr. Setzer said that between June and October 1987, covering the whole dry season, the satellite registered more than 350,000 fires. Because burnings may last between 24 and 48 hours, many fires may have been registered more than once, Dr. Setzer said. Therefore, he added, his group is using a conservative estimate of 170,000 fires for 1987.

As part of the new program, researchers send their findings every day to the National Forestry Service in Brasília. Shocked by last year's data, the service has said that this year it will open a nationwide campaign and levy large fines for the burnings. Virtually all the fires are conducted illegally, without the required permits.

But the service, which guards the largest forest on earth, has fewer than 900 wardens for a region larger than Europe. "We would need 15,000 to 20,000 guards to be effective," said Carlos Marx Carneiro, a director of the service.

Ambitious Amazon Expedition Probes Forest's Role in Global Atmosphere

Project employs new technology to get best data yet.

By **MARLISE SIMONS**

MANAUS, Brazil

SHORTLY after dawn, the Electra climbed above the Amazon River, nudged through plumes and layers of steam, then bumped along just 500 feet over the jungle canopy. On board, a phalanx of scientists started probing the breath of the forest.

Laser beams shot through openings on the roof and floor of the aircraft, measuring gases at different levels. Thin pipes sucked samples of air into gas detectors. Down below, a network of investigators in weather stations, towers and ships examined the forest soil and water and the gases emerging from the lush ecosystem.

The scientists, from the United States and Brazil, were participating in the most ambitious expedition ever mounted to study the chemistry of the tropical forest and atmosphere. This research is part of a worldwide project, sponsored by the National Aeronautics and Space Administration, that aims to quantify for the first time the contribution of the earth's living systems to key compounds in the atmosphere — compounds that in turn help regulate climate and life.

Scientists give high priority to improving knowledge of the rain forest's role in these processes. To understand the earth's chemistry, it is essential "to couple the forest to the atmosphere," said Dr. Robert J. McNeal, a NASA scientist who is a manager of the global research project.

Here in the world's largest tropical forest, the key questions include these: Just how much does the forest produce and consume of a host of gases and particles that play important roles in the atmosphere? What is the global impact of the intense tropical storms that constantly mix and turn over these compounds, pushing some up into the upper atmosphere and pulling others down to the jungle? How does the vast rain forest influence levels of gases that may contribute to global warming or that destroy the stratospheric ozone that shields the earth from dangerous ultraviolet radiation?

Many of the elemental cycles of the forest, water and air ~~are known~~ in a ~~general way.~~ The giant trees of the rain forest, for example, absorb carbon dioxide as they grow but release it to the atmosphere when they burn or rot. Plants and animals in the forest soils and waters produce nitrous oxide, which can be transformed into ozone destroyers in the upper atmosphere. At the same time, the forest vegetation itself destroys ozone near the ground, where it is a pollutant.

But the exact quantities of these and many other compounds the forest exchanges with the atmosphere are unknown, and the scientists here are hoping the data they gather will complete some of these crucial equations. "The existing models are based on guesswork and small-scale experiments," said Dr. McNeal.

The Amazon expedition, conducted with Brazil's National Institute for Space Research, is one of the early phases of NASA's Global Tropospheric Experiment. NASA has conducted two expeditions in the Amazon and another in Barbados; work will begin next on the Arctic tundra and over the equatorial Atlantic and Pacific Oceans. NASA also hopes to extend its program to China to measure the high methane emissions over the country's extensive rice paddies and the impact of the Gobi's dust storms.

Industrial activities are producing carbon dioxide and other gases that trap heat like a greenhouse, raising the earth's temperature. Scientists believe that man-made chemicals are helping deplete the ozone of the upper atmosphere.

But nature, too, emits and absorbs many compounds, including various "greenhouse" gases, ozone, and ozone-destroying compounds. While specialists have learned a great deal about man-made pollution, they still know little of the atmospheric role of natural ecosystems. Such knowledge is important both for understanding current trends and for predicting the consequences of such changes as the large-scale clearing of the Amazon and other rain forests.

"Atmospheric science is a new frontier that requires new ways of thinking, new techniques," said Dr. Robert Harriss of NASA. "We are dealing with a whole new set of issues. There is almost nothing in the textbooks about this."

The Amazon tests have been made possible now only by the development of new instruments that can measure gases and particles on the smallest scales. For instance, a new laser system devised at NASA is able to picture ozone all the way from the forest to an altitude of 40,000 feet.

In addition, the six-week expedition, which ended May 15, brought together an unusually diverse group of 60 Americans and 90 Brazilians, including geochemists, physicists, biologists and meteorologists, working at 20 different sites. In a gigantic logistical operation, tons of equipment from the United States was moved up the Amazon by ship. Sometimes things simply bogged down when no bulldozer could be found to move heavy gear up the mud roads.

Between field trips and flights, the experimenters compared notes here in the heart of the Amazon basin, a place where heat and humidity cling to everything like a sheen of oil. In rooms full of computers and maps, there were daily meetings with meteorologists who received satellite pictures of the rain forest every 30 minutes from NASA offices in Langley, Va.

"We are trying to see how the whole clockwork functions," said Meinrat Andreae of Florida State University. "There are wheels within wheels in a very complex mechanism and only by scrutinizing all the parts can we understand it."

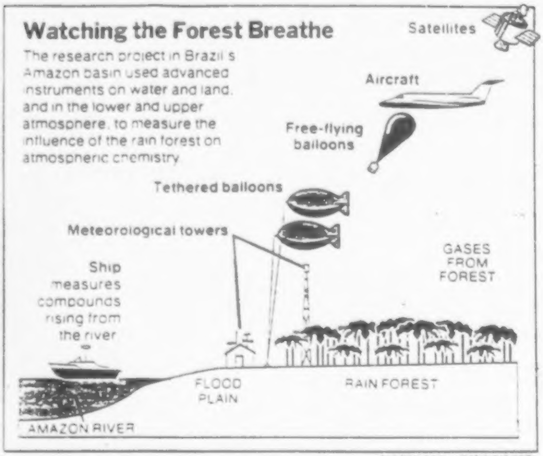
The scientists will be interpreting their data for months, but some felt they had already gained significant insights. Differences between the wet and the dry season, for example, have proved so great that existing studies based largely on the dry months are now seen as misleading.

New York Times, June 2, 1987, pp. C1, C9

© 1987 The New York Times. Reproduced by the Library of Congress, Congressional Research Service with permission of copyright claimant.

The New York Times/Marlise Simons

Virgle Rabine piloting the Electra over the Amazon.



Watching the Forest Breathe

The research project in Brazil's Amazon basin used advanced instruments on water and land, and in the lower and upper atmosphere, to measure the influence of the rain forest on atmospheric chemistry.

The New York Times/Steve Hart

At one forest site northwest of Manaus, tests were in progress 24 hours a day. Free-flying balloons carrying instruments and a radio transmitter were launched every three hours to register ozone, temperature, moisture. Tethered balloons hovered at 500 meters and 1,500 meters, sometimes dancing wildly in the wind. Instruments on the ground and up on towers monitored the breath of the jungle day and night as it came off the mud, the debris, the living forest, and then rose up through the canopy.

"Plants do extremely weird things — they throw off gases and shed particles from their leaves that are one-thousandth of a millimeter in size," said Paulo Artaxo, a Brazilian nuclear physicist who examines such particles or "aerosols" in a nuclear accelerator. "These plant aerosols are made of potassium, phosphorus, calcium, sulfur and chloride. We want to know how they are generated, change, get into the rain. Because the Amazon is so big it throws tons of these into the air."

Working from a 45-meter tower, where he watched green, red and blue macaws skim along the treetops, Steven Wofsy of Harvard University found that gas emissions could be identified and measured; he was able to quantify nitrogen produced in the tropical soil.

"Nitrous oxide is an important gas influencing the ozone layer in the stratosphere," he said. "We found the emissions in the ocean and the Northern Hemisphere to be very small. They are very substantial here." But to infer the forest's total emissions, he said, would be complicated. "Heavy rains have a great effect on the soil," he said. "We found the emissions shut down and could take two days to come back up again."

In the silent understory, a slender metal structure holding up a solar panel and a radio transmitter incongruously competed for light with trees a hundred feet high. "This is beaming climate data, first up to a satellite, then to Boulder, Colorado," said James Hoell, a NASA project manager.

Experimenters have registered some of the purest air and rainwater on record, testifying to the jungle's cleansing efficiency.

Dr. Andreae's measurements of the forest sulfur cycle led him to suggest that natural systems, like the forest, do not produce high sulfur emissions. "Emission of hydrogen sulfide and other sulfurs we found here were not only very low," he said, "they were 10 times lower than the extrapolations people had made in the U.S." from incomplete data.

For such experiments, instruments had to be specially adapted or designed. "Equipment available was suited for polluted atmospheres," said Dr. Andreae. "Here you can be measuring concentrations a thousand times lower. Much of the rain was clean as distilled water."

Equally striking, he said, was the rain's high acidity in earlier tests in the dry season. The acid levels resembled those in acid rain in the United States, but these naturally produced acids, in contrast with those deriving from industrial pollution, quickly break down, he said.

Many expedition scientists were excited by their more sophisticated sensing of ozone, the understanding of which is a fundamental goal of this NASA program. While ozone provides a shield against radiation in the stratosphere, it is considered a pollutant at the earth's surface.

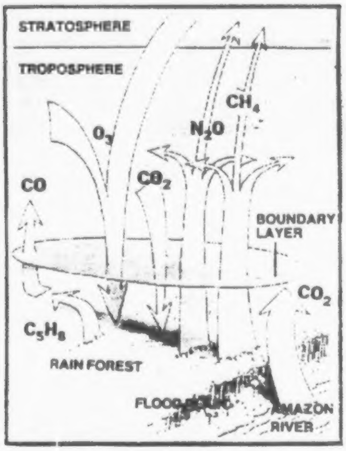
Burnings to clear forests and fields produced a lot of ozone in the dry season, said Dr. Harriss. "But the rain forest is unique in destroying the polluting ozone. When it comes in contact with a surface like a leaf, it oxydizes and is consumed."

Ozone concentrations of 4 parts per billion found here over extended periods in the wet season, he said, were among the lowest in the world. "In any big city it is 10 to 100 times higher," he said.

The most dramatic experiments were conducted on the plump 1961 Electra, an "electronic fleamarket" containing a new system of lasers, mirrors and telescopes, uniquely capable of detecting ozone and other particles from the ground up to 40,000 feet. Its creator, Edward V. Browell of NASA, used the data to make color charts of atmospheric levels.

As the Electra circled low over the forest, turbulence and 90-degree heat caused by computers and compressors made the passengers weary. The discomfort was offset by majestic views of nature's lushest stronghold — the Amazon basin, encompassing seven million square kilometers of jungle, savannas and wetlands and a grid of 1,100 rivers.

Also in view were the widening scars of land stripped bare for cattle and sugar cane — harbingers of a trend that, if unchecked, will ravage much of the rain forest, altering the world's atmosphere as well as destroying an unparalleled natural treasure.

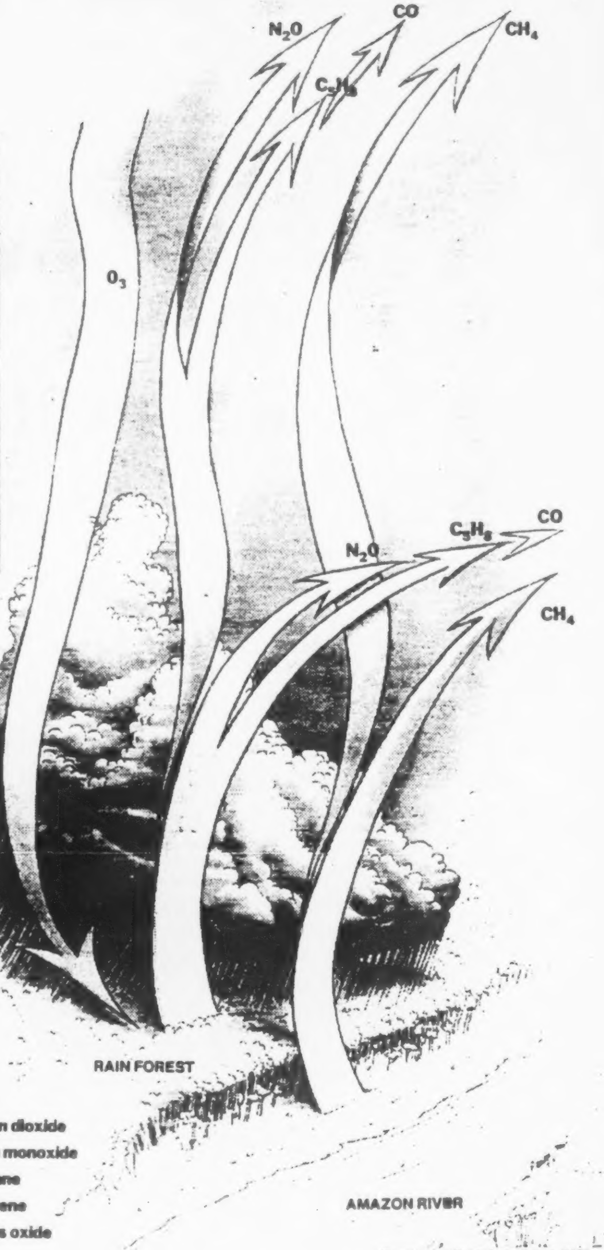

STRATOSPHERE
TROPOSPHERE
O_3
CH_4
N_2O
CO
CO_2
BOUNDARY LAYER
CO_2
C_5H_8
RAIN FOREST
FLOODPLAIN
AMAZON RIVER

A quiet day above the jungle

Normally, above, most gases produced by the forest remain below the boundary layer that forms where warm and cold air meet less than a mile above the ground. Longer-lived gases slowly make their way into the upper troposphere, where they can circulate globally, and some eventually reach the stratosphere. The forest breaks down ozone from the atmosphere and absorbs carbon dioxide.

A tropical storm's global impact

In a tropical storm, right, the boundary layer disappears. Forest gases are more easily pumped into the upper troposphere, altering the chemical balance worldwide. Some forest gases including nitrous oxide, methane and carbon monoxide contribute to the warming of earth through the greenhouse effect. Nitrous oxide also forms compounds that destroy the protective ozone layer in the stratosphere.


N_2O
CO
CH_4
C_5H_8
O_3
N_2O
C_5H_8
CO
CH_4
RAIN FOREST
AMAZON RIVER

O_3 = ozone
CO_2 = carbon dioxide
CO = carbon monoxide
CH_4 = methane
C_5H_8 = isoprene
N_2O = nitrous oxide

Illustrations by Randy Jones; Source: NASA

The Significance of the Amazon Basin for Global Climatic Equilibrium

by Peter Bunyard

Tropical forests play a vital role in regulating the world's climate. Not only will their loss reduce evapotranspiration, thus disrupting the global hydrological cycle, but it will also alter the chemistry of the atmosphere, adding appreciably to the amount of CO_2 and other gases in the atmosphere. Although the precise long-term outcome is unpredictable, the destabilisation of the climate seems a certainty.

Like other stars, the sun is getting hotter as it ages, the main reason being the formation of a helium layer which acts as a blanket keeping in the heat and thereby speeding up the thermonuclear process. Atmospheric carbon dioxide concentrations were hundreds of times greater early on in the earth's history. Such high concentrations at a time when the sun had a solar constant 70 per cent of the present day may have been vital for keeping the Earth warm enough to have enabled the evolution and development of life. The dumping of carbon dioxide by photosynthesising organisms, initially the cyanobacteria, may well have been a crucial process in the maintenance of a planet with a tolerable climate for life to continue.

Our disturbance of that natural process is likely to have profound effect on global climate. The burning of fossil fuels leads to the annual release of approximately 5 billion (10^9) tonnes of carbon each year into the atmosphere, some 60 billion tonnes overall having been released between 1850 and 1950. Calculations[1] indicate that worldwide deforestation injects between 5 and 10 billion tonnes of carbon into the atmosphere each year, with 3 to 6 billion tonnes coming from the destruction of tropical forests alone. Such estimates are contingent on the forest biomass being converted into gases through burning and other oxidation processes. The oxidation of forest humus releases in the region of 2 billion more tonnes of carbon each year.

Of all the carbon dioxide injected into the atmosphere, some 50 per cent remains in the atmosphere, the rest having been absorbed into the oceans or actively taken up by marine algae (coccolithophorids for example) and converted into calcium carbonate. Moreover, the increase in primary photosynthetic production stimulated through the accumulation of carbon dioxide in the atmosphere is far from compensating for the quantities discharged each year through fossil fuel burning and deforestation. Thus the increased photosynthetic productivity worldwide brought about through the one part per million per annum increase in atmospheric CO_2 is likely to give a maximum of 0.24 billion tonnes of carbon—hence less than one-tenth of the quantities released through clearance of tropical forests.

CO_2 and the Greenhouse Effect

The importance of CO_2 as a greenhouse gas is now generally accepted. Today, with a warmer sun compared with previous aeons, the equilibrium temperature at the top of the earth's atmosphere is found to be approximately 267 K or −16°C. Yet the average temperature at the earth's surface is 288 K or 15°C, therefore more than 30°C hotter, thus enabling the survival of much of life on earth. Climatologists expect atmospheric carbon dioxide levels to double in the next century compared to the 260 ppmv* of the early 1800s. A doubling of the CO_2 leads to an extra 1.5 per cent of solar radiation being trapped—hence equivalent to placing a 15 watt light bulb every four square metres over the surface of the earth. Equally significant, the effect of doubling CO_2 on the global energy balance is some 80 times greater than the heat generated by the burning of fossil fuels or of the forest that gave rise to the CO_2 in the first place. The general consensus is that a doubling of the CO_2 content in the atmosphere will lead to a 2 to 3°C increase in the globally averaged surface air temperature. There may be some compensation in terms of greater cloud cover through enhanced evaporation, the cloud cover raising the albedo and hence the reflectivity of the earth's surface. On the other hand, as I shall show, the loss of forest, particularly in the Tropics, may lead to a considerable diminution of evapotranspiration. A significant drying out of the moist Tropics may therefore be one consequence of deforestation.

Evapotranspiration and Deforestation

Research in the Amazon in particular has revealed the remarkable efficacy of the intact forest in returning moisture to the atmosphere. According to E. Salati and his colleagues,[2] approximately 50 per cent on average of the rain falling over the Amazon Basin is both evaporated and transpired: in some regions, for instance close to Manaus, the amount being returned through evapotranspiration may be as high as 75 per cent. Since the rainfall over the equatorial region tends to be high, the total amounts of water being returned to the atmosphere are considerable. Estimates indicate that 12 trillion (10^{12}) cubic metres of rain fall over the Amazon Basin each year, of which 6.5×10^{12} is evapotranspired.

The vaporisation of such large quantities of water absorbs very large quantities of energy in terms of solar heat. According to Luiz Molion, on dry days 75 per cent of the absorbed radiative energy is consumed in evapotranspiration and the remaining 25 per cent in heating the air. Hence the vapour returned to the atmosphere exerts a considerable cooling effect, equivalent to perspiration, on the total surface environment.

A number of crucial questions follow such discoveries. How much re-

---

*part per million volumemetric.

Mark Edwards—Still Pictures/Panos Pictures

Deforestation is already having a significant effect on local climate, causing forests downwind of encroachments to dry out.

cycling of water goes on over the Amazon Basin, and how essential is the forest upwind for the watering and integrity of the forest downwind? Will massive deforestation in one part of the Amazon Basin lead to a drying out and decimation of that in other parts? Salati and his co-workers have found through investigation of the movement of the oxygen isotopes 16, 17 and 18 (mass number) that recycling of water from east to west across the Amazon Basin plays a significant role in the watering of the forest. Salati is concerned that this recycling mechanism will be perturbed if not jeopardised through the wholesale destruction of the forest. And because of poor soils of Amazonia, regeneration of adequate forest may take one thousand years or more.

Experiments carried out by Judy Rankin in the Amazon Basin indicate that isolated patches of forest of even up to 1000 hectares cannot be self sustaining, in marked contrast to patches of forest in temperate zones. Thus Rankin found that within a couple of years of the forest being cleared around the intact patches degradation sets in starting at the edges and moving in. Winds penetrating the forest and uprooting trees are one factor; drying out is another. Disturbance of flowering and fruiting through disruption of the co-existence of animals and plants may well be another destructive force.

The climatic consequences of the loss of tropical forest are considerable. A substantial proportion of the evapotranspired vapour is carried either side of the intertropical convergence zone high into the trophosphere and then towards higher latitudes where it gets caught up in the Hadley Cell circulation of winds that move first eastwards—the westerlies—and then return to the Americas as the trade winds. On precipitation, the latent heat bound up in vaporisation is released, some 560 calories per gram. In that way heat is transferred from the Tropics to the higher latitudes thus contributing significantly to a more equitable climate in temperate areas. In effect, without the tropical forest, and that of the Amazon Basin in particular, the Tropics would tend to be hotter and drier and the temperate regions both sides of the equator colder. The moist tropical forests of the world can therefore be considered as a vital component in the process of pumping heat from the hot regions of the globe to the cooler regions.

The transfer of heat through vaporisation followed by precipitation is considerable. Professor Jan Peagle points out that 2 centimetres of rain is sufficient to heat the entire trophosphere by some 6°C. During peak rainfalls exceeding 6 cm, the heat released is sufficient to warm the trophospheric column of air above the earth by as much as 20°C. Meanwhile sensible, direct heat from the sun over the course of a day can only warm up the air column by less than 2°C.

Changing Atmospheric Chemistry

Deforestation is likely to lead
subtle though consequential chan
in the chemistry of the atmosph
As Paul Crutzen[3] points out,
tropical atmosphere generate
highly reactive chemical radi
produced through the photolysi
ozone by means of ultraviolet r
ation. That radical, known
hydroxyl, is present in minute qu
tities, its mixing ratio being 2 x 1
yet it is responsible for the remov
many trace gases from the atm
phere, in particular methane and
bon monoxide, but including hy
gen sulphide, the nitrogen ox
and almost all organic gases.
these, after reacting with hydr
form highly soluble products that
efficiently scavenged by rain fall.

Man's activities in the tropics
having a significant effect on atm
pheric chemistry. In particular
chopping down of trees and
burning is increasing the burde
both carbon monoxide and carbo
oxide in the atmosphere, while
creased rice production is ad
substantially to the amount
methane being liberated from
soil. Cattle ranching as well as
mite activity, enhanced through
ing the forest, are also responsibl
methane production, cattle addin
atmospheric methane through be
ing.

Around 2-3 million hectares
year are now cleared in the Am
Basin alone for annual crops and
tures, well over 100,000 square
metres having been cleared in
region for cattle between 1966
1983. In terms of methane rele
into the atmosphere, estimates
cate that they amount to 380Tg (
grams or 10^{12}g) per year, divided
the following categories: dom
ruminants 80Tg; biomass bur
45/60Tg; natural gas leaks 33Tg;
mining 34Tg; rice paddies 120Tg;
natural wetlands 70/50Tg.

The annual growth rate in w
wide cattle population in the de
between 1970 and 1980 was app
mately 1 per cent; in coal and na
gas production 2.2 per cent an
rice paddy area about 0.7 per
According to Crutzen, methane
creasing in the atmosphere by a
1.2 per cent per year suggestin
annual growth of 4.6Tg, and t

fore 1.6 per cent of the total anthropogenic source. The annual increase in methane emissions as a result of rice paddy, cattle production and fossil fuel use amounts to some 2.9Tg, leaving 1.7Tg unaccounted for. Biomass burning will account for some of that difference, but Crutzen suggests that increased methane in the tropical atmosphere is reducing the concentration of hydroxyl and therefore effectively reducing the oxidative and cleansing powers of the atmosphere in that part of the globe.

Laboratory experiments indicate that for each methane molecule oxidised in environments which are poor in nitric oxide (NO) 3.5 hydroxyl radicals are consumed as well as 1.7 ozone molecules. Equally, when carbon monoxide, largely produced from biomass burning in the Tropics, is oxidised by hydroxyl in an NO_x—poor atmosphere, such as one finds over the equatorial region, both hydroxyl and ozone are consumed.

The net result of these oxidations in the tropical environment is that the oxidative powers appear to be constantly diminishing. The overall effect of that change remains to be seen.

The situation has become markedly different over the industrial areas of the northern latitudes. There fossil fuel burning has led to the release of NO_x, particularly nitric oxide, as well as of unburnt hydrocarbons. Where NO levels are high the oxidation pathway takes a different turn, the nitric oxide effectively catalysing the production of both hydroxyl and ozone. Thus when methane is oxidised in a NO-rich atmosphere via carbon monoxide half an odd hydroxyl radical is generated as well as 3.7 ozone molecules. The atmosphere over industrial areas has therefore become more powerfully oxidising, one consequence being an acceleration in the oxidation and deposition of acid oxides such as sulphur dioxide and nitrogen oxides.

Increasing Instability

Overall, what are the implications of increasing hydrocarbons such as methane in the atmosphere? First, a loss of oxidative powers over the Tropics is leading to the gradual build-up of various gases such as methyl chloride and methyl chloroform which would otherwise swiftly get oxidised and scavenged. These gases will now increasingly pass into the stratosphere where they serve as precursors for chlorine production, the chlorine being able to interact with ozone.

Moreover, because methane is increasing by more than one per cent each year, the imbalance between hydroxyl production and its destruction will increase, further diminishing the oxidative powers of the atmosphere. On the other hand, methane destruction may increasingly take place in higher latitudes where the NO concentration is greater because of man's industrial activities. Thus, there may be an increasing tendency to lose ozone in clean, tropical atmospheres and to generate it in polluted areas. The loss of ozone in tropical areas will be accentuated by the production of chlorine and water vapour, whereas its production over industrial areas will accelerate acid deposition, whether the source of the acid precursors is bio- or anthropogenic.

Man's activities in the tropics are having a significant effect on atmospheric chemistry.

In conclusion, deforestation in the Amazon Basin may well lead to significant changes to global climate through perturbing the hydrological cycle, while equally altering atmospheric chemistry and contributing to enhanced oxidation processes in the atmosphere over industrial areas.

Notes:
1. Ramade, R. *The Ecology of Natural Resources,* (Wiley) 1984.
2. Salati, E. *The Geophysiology of Amazonian Vegetation and Climate Interaction,* Chapter 15, pp 273-296, (Wiley) 1987.
3. Crutzen, Paul, supra note 2, Chapter 8, pp 108-130.

LONDON ECOLOGY CENTRE

45 Shelton Street, Covent Garden tube
NEW ECOLOGY SHOP

The Centre's new shop sells a wide range of books on topical issues ranging from nature conservation and energy to vegetarian cookery and green politics; also journals, education packs, posters and postcards plus attractive recycled stationery.

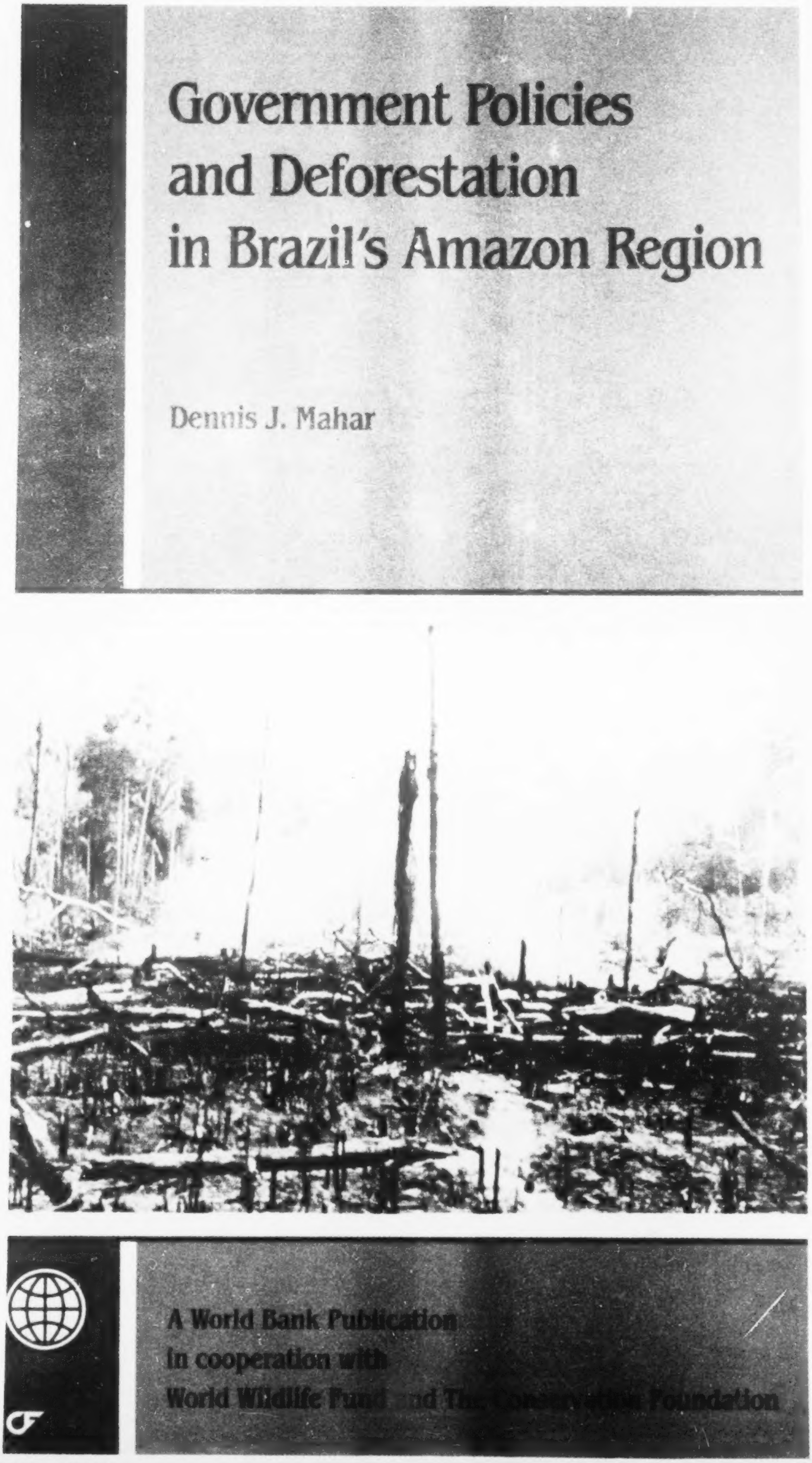
This new shop will also include London's only RSPB outlet:

RSPB
THE ROYAL SOCIETY FOR THE PROTECTION OF BIRDS
BirdShop

Here you will find everything you need to turn your garden into a haven for wildlife: nestboxes, birdseed, batboxes and a beautiful collection of wildflower seeds. A selection of RSPB gifts and birdwatching equipment will also be available.

This exciting new venture adds a new dimension to the Centre's existing facilities. We have a wholefood café, information service and an exhibition gallery with a full programme of events on an environmental theme.

Please ring (01) 379-4324 for details
MONDAY — SATURDAY, 10 am — 6 pm



Government Policies and Deforestation in Brazil's Amazon Region

Dennis J. Mahar

A World Bank Publication
in cooperation with
World Wildlife Fund and The Conservation Foundation

Government Policies and Deforestation in Brazil's Amazon Region

Dennis J. Mahar

World Wildlife Fund and The Conservation Foundation
Washington, D.C.

Published by arrangement with The World Bank

Dennis J. Mahar is an adviser on the Economic Advisory Staff of the World Bank. He wishes to thank Luis Coirolo, Louise Fox, Robert Goodland, Peter Knight, Maritta Koch-Weser, Ernst Lutz, and Stephen Weissman for their valuable comments on drafts of this study and John McKenna, Richard Norgaard, Robert Repetto, and John Wilson for their help in obtaining certain data and reference materials. He also gratefully acknowledges the support of Vinod Dubey, director of the Economic Advisory Staff, as well as the Environment and Brazil Country Departments of the World Bank.

The cover photograph (by Douglas R. Shane/World Wildlife Fund) depicts the burning of rain forest in Rondônia, Brazil, to make way for rangeland.

The views and interpretations in this pamphlet are those of the author and do not necessarily represent the views and policies of the World Bank or of its executive directors or the countries they represent.

© 1989 The International Bank for Reconstruction
and Development / The World Bank
1818 H Street, N.W.
Washington, D.C. 20433, U.S.A.

All rights reserved
Manufactured in the United States of America
First printing January 1989

ISBN 0-8213-1174-3

Contents

Acronyms and Abbreviations *v*

Introduction *1*

Brazil's Amazonian Forests *3*
  Biological Diversity *5*
  The Magnitude and Rate of Deforestation *5*
  Proximate Causes of Deforestation *7*

The Evolution of Regional Policies *9*
  Operation Amazonia *10*
  The Belém-Brasília Highway *12*
  Incentives for Livestock Development *13*
  The National Integration Program *23*
  The Cuiabá-Pôrto Velho Highway and POLONOROESTE *28*
  The Era of Big Projects *40*

Conclusions and Recommendations *45*

References *50*

Boxes

Box 1. The Amazonian Rubber Boom *10*
Box 2. The Rondônia-Paraná Connection *30*

Figures

Figure 1. Amazonian Road Network, 1960–85 *23*
Figure 2. Average Land Prices in Rondônia, 1978–86 *38*

Maps

Map 1. Amazon Region of Brazil *4*
Map 2. Deforestation in Southeast Pará, 1972, 1977, and 1985 *14*
Map 3. Amazonia: Main Federal Highways *24*
Map 4. Deforestation in Rondônia, 1983 *32*

Tables

Table 1. Landsat Surveys of Forest Clearing in Legal Amazonia *6*
Table 2. Agricultural Land Use in Legal Amazonia, 1980 *8*
Table 3. Internal Rates of Return to a Typical SUDAM-Approved Livestock Project under Two Scenarios *17*
Table 4. Commitments of Official Rural Credit in Classic Amazonia, 1970–85 *21*
Table 5. Agricultural Land Use in Rondônia, 1970–85 *35*

Acronyms and Abbreviations

AEA	Association of Amazonian Entrepreneurs
BASA	Bank of Amazonia
CVRD	Companhia Vale do Rio Doce
FAO	Food and Agriculture Organization
FAO/CP	Food and Agriculture Organization/World Bank Cooperative Program
FINAM	Amazon Investment Fund
IBDF	Institute of Forestry Development
INCRA	National Institute for Colonization and Agrarian Reform
IPEA	Institute of Economic and Social Planning
IRR	internal rate of return
ITR	rural land tax
PGC	Greater Carajás Program
PIN	National Integration Program
POLAMAZONIA	Program of Agricultural, Livestock, and Mineral Poles in Amazonia
POLONOROESTE	Northwest Brazil Integrated Development Program
PROPEC	National Program of Livestock Development
PROTERRA	Land Redistribution Program
RADAM	Radar in Amazonia Project
SUDAM	Superintendency for the Development of Amazonia

The world's tropical rain forests are disappearing at an alarming rate. These forests once occupied 16 million square kilometers of the earth's surface, but now cover only 9 million. It is estimated that Latin America and Asia have already lost 40 percent of their original forests, and Africa a little more than half (Myers 1984). In many countries the rate of deforestation is accelerating: most of the forested areas of Bangladesh, India, the Philippines, and Sri Lanka, and parts of Brazil's rain forest, for example, could be gone by the end of this century. Only in the Congo Basin and some of the more isolated areas of the Amazon Basin does the forest remain largely intact.

To be sure, deforestation of this magnitude has in some instances yielded considerable short-term benefits through timber exports and agricultural production on previously forested land. But it has entailed huge (and largely unmeasured) long-term costs for both the people of the countries directly affected and the human race as a whole. Among the more direct and visible costs of tropical deforestation are the losses of forest products such as timber, fuelwood, fibers, canes, resins, oils, pharmaceuticals, fruits, spices, and animal hides. Less direct, but equally important, long-term costs are soil erosion, flooding, and the siltation of reservoirs and hydroelectric facilities; the destruction of wildlife habitat; and climatic changes associated with the removal of forest cover in tropical regions. Perhaps the single most important long-term cost of deforestation, however, is the irreversible loss of biological diversity.

No one knows how many species inhabit the planet. Tropical rain forests, however, are thought to contain about half of the earth's estimated 5 million to 10 million species on just 7 percent of its land surface. The richness of life in these forests is remarkable. The Amazon rain forests, for example, support 30,000 species of plant life, whereas only an estimated 10,000 species can be found in all of temperate South America. Northern forests, in contrast, normally contain only ten to fifteen species of plant. The variety of insect life in the rain forest is even more striking. Scientists have discovered and named roughly 1 million insect species worldwide. One scientist, however, extrapolating from surveys of the rain forest canopy in Panama, estimates that there may be as many as *30 million* insect species in tropical forests alone (Wolf 1988, p. 104).

Many of the species native to tropical rain forests have proved invaluable to humankind: for example, drugs (vincristine and vinblastine) developed within the past two decades from a wild periwinkle found in the forests of Madagascar have dramatically improved the effectiveness of treatment for leukemia and other forms of cancer. Since fewer than 1 percent of tropical plants have been screened for potentially useful properties, ongoing deforestation will result in the permanent loss of other species before their value to humankind is recognized (World Resources Institute 1985). It has been estimated that 15 percent of all plant species in Latin American rain forests will become extinct by the end of this century if present rates of clearing continue; under a "worst case" scenario which assumes an acceleration in the rate of deforestation, as many as two-thirds of the species could suffer this fate (Wolf 1988, p. 103).

The proximate causes of tropical deforestation vary significantly among regions of the world and even within countries. Most experts agree, however, that the spread of small-scale agriculture is the most important of these. According to Myers (1986), this type of activity leads to the depletion of about 150,000 square kilometers of forest every year.[1] Other major proximate causes are commercial logging (45,000 square kilometers a year), fuelwood gathering (25,000 square kilometers a year), and cattle raising (20,000 square kilometers a year). Such facts are useful to know, but it is far more important to be aware of the *underlying* causes of forest destruction. Holding the small farmer responsible for tropical deforestation is tantamount to "blaming the victim," because the real causes are likely to be poverty, unequal land distribution, and low agricultural productivity combined with rapid population growth. To this list one must add misguided public policies which purposely or inadvertently encourage rapid depletion of the forest (see Collins 1986 and World Resources Institute 1985).

---

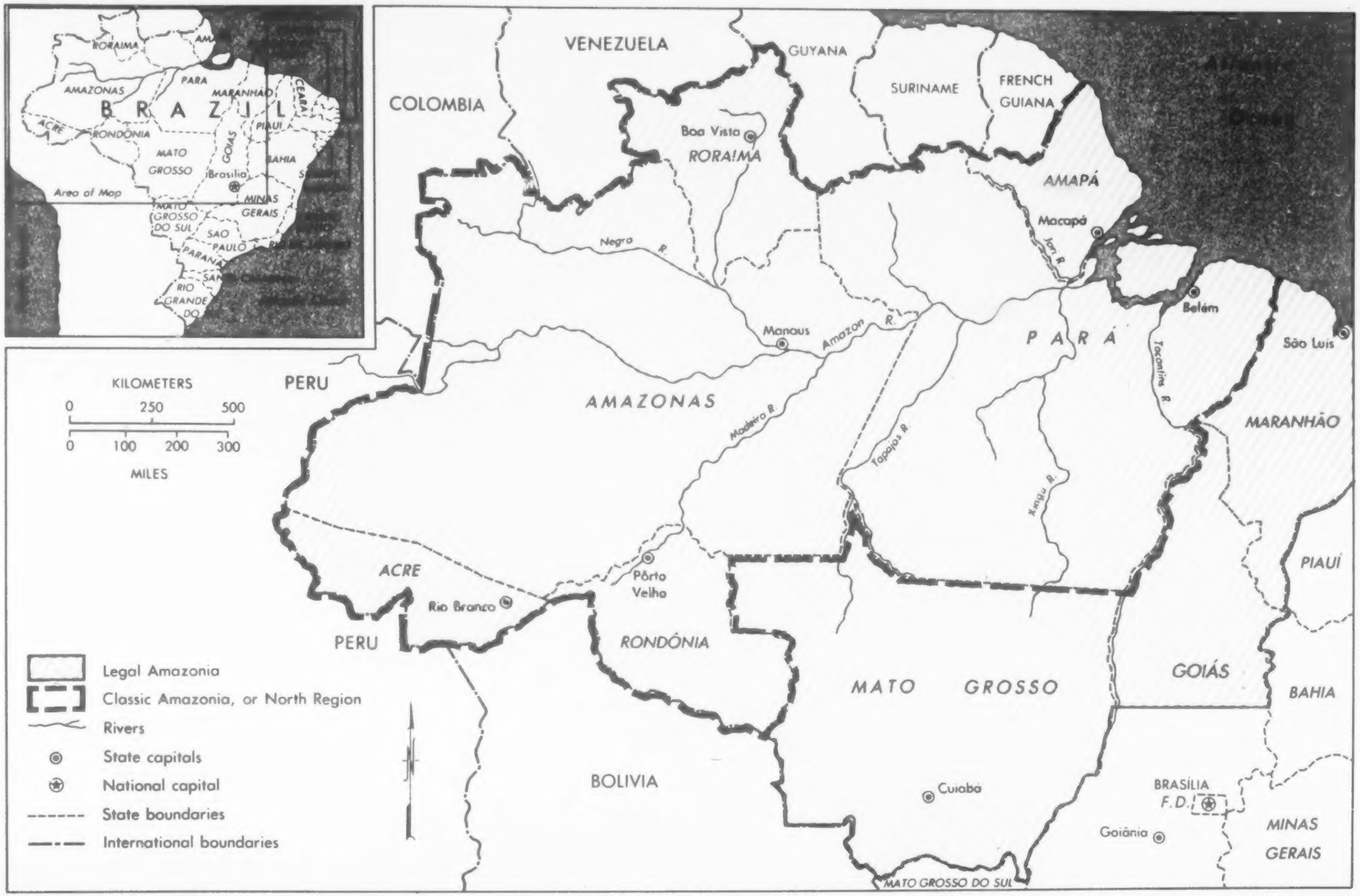
[1] The term "depletion" refers to both "deforestation" (a complete and permanent removal of all forest cover) and "major disturbances" (any modification of the forest, such as selective logging, that leads to a pronounced impoverishment of the forest ecosystem). An estimated 200,000 square kilometers of tropical forest are depleted each year. Deforestation amounts to about 70,000–90,000 square kilometers a year worldwide.

The underlying causes of tropical deforestation have not been thoroughly researched and, as a result, are not completely understood. The purpose of this pamphlet is to shed further light on the subject by analyzing the effects of certain government policies on deforestation in the Brazilian Amazon. The coverage is far from complete. The emphasis is on policies which encourage economic activities that are detrimental to the environment and on those subregions that are now experiencing the most rapid deforestation. The equity aspects of these policies are also considered. The principal message is that attempts to reduce or stop tropical deforestation by fiat *only*—for example, through land-use zoning, legislation establishing national parks, or legal prohibitions of certain types of economic activity—are not likely to succeed if economic incentives encourage people to do the opposite.

Brazil's Amazonian Forests

According to estimates from the Food and Agriculture Organization (FAO), Brazil contains about 3.5 million square kilometers of tropical forest (Guppy 1984, p. 930). This is equivalent to 30 percent of the world total and is more than the combined forested areas of Colombia, Indonesia, Peru, and Zaire. Almost all of Brazil's standing tropical forests are in the Amazon Basin, a region commonly known as Amazonia. Two geographical concepts of Amazonia are used in Brazil—Legal Amazonia and Classic Amazonia (see map 1). As legally defined for purposes of regional planning and policy, Amazonia has an area of just over 5.0 million square kilometers, which is about 58 percent of Brazil's total land area. Legal Amazonia comprises seven states and territories (Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, and Roraima) and parts of two others (Goiás and Maranhão). Classic Amazonia (also known as Brazil's North region), as defined for statistical

Map 1. Amazon Region of Brazil


RORAIMA
AMAZONAS
PARA
MARANHÃO
CEARA
B R A Z I L
ACRE
RONDÔNIA
PIAUI
MATO GROSSO
GOIAS
BAHIA
Brasilia
Area of Map
MATO GROSSO DO SUL
MINAS GERAIS
SAO PAULO
PARANA
RIO GRANDE DO
VENEZUELA
GUYANA
SURINAME
FRENCH GUIANA
COLOMBIA
Boa Vista
RORAIMA
AMAPÁ
Macapá
Jari R.
Negro R.
Belém
São Luis
Manaus
Amazon R.
P A R Á
Tocantins R.
PERU
AMAZONAS
Madeira R.
Tapajos R.
Xingu R.
MARANHÃO
PIAUÍ
ACRE
Pôrto Velho
Rio Branco
PERU
RONDÔNIA
MATO GROSSO
GOIÁS
BAHIA
BOLIVIA
Cuiaba
BRASÍLIA F.D.
Goiânia
MINAS GERAIS
MATO GROSSO DO SUL
KILOMETERS
0
250
500
0
100
200
300
MILES
Legal Amazonia
Classic Amazonia, or North Region
Rivers
State capitals
National capital
State boundaries
International boundaries

purposes, comprises only six states and territories and is 1 million square kilometers smaller. Because the focus of this pamphlet is on government policy, to the extent possible and unless otherwise stated, the designation "Amazonia" in this pamphlet refers to the legal definition. About half of Amazonia (2.5–2.8 million square kilometers) comprises upland areas (*terra firme* in Portuguese) in which the original vegetation was tropical rain forest (Fearnside 1986b). Perhaps another 500,000 square kilometers consists of transitional forests (U.S. Department of Energy 1986). There are in addition large areas of savanna (*cerrado*) in the southern reaches of Amazonia in Mato Grosso and Goiás.

Biological Diversity

Amazonia has been characterized as the "single richest region of the tropical biome" (Myers 1984, p. 50). Indeed, the region's forests, air, soils, and water literally teem with life. A single hectare of rain forest near Manaus, Amazonas, for example, yielded 235 tree species over 5 centimeters in diameter and 179 species over 15 centimeters in diameter (Prance 1986). The quantity and variety of bird, fish, and insect life are also unmatched. There are, for instance, 2,000 known species of fish in the waters of the Amazon Basin. This is eight times the number of species in the Mississippi River system and ten times the number found in all of Europe. And this represents only the *known* species; experts think that the total may eventually reach 3,000 species. Most scientists agree that deforestation is greatly reducing this natural variety and is thereby depriving some regional populations of their livelihoods[2] and humankind of as-yet-undiscovered medicinal plants or pest-resistant genetic materials.

The Magnitude and Rate of Deforestation

The first scientific estimates of deforestation in Amazonia were made in the early 1970s by staff of the federal government's Radar

---

[2] Michael Goulding, in a pioneering study of Amazonian fisheries (Goulding 1983), found that most of the commercial species feed on fruits, seeds, insects, and detritus from the annually flooded forests. He concluded that the conversion of these forests to agricultural land or other purposes would greatly reduce the commercial catch as well as the quantity of species of less commercial importance.

Table 1. *Landsat Surveys of Forest Clearing in Legal Amazonia*

		Area cleared							
		Square kilometers				*Percentage of state or territory*			
State or territory	*Area (square kilometers)*	*By 1975*	*By 1978*	*By 1980*	*By 1988*	*By 1975*	*By 1978*	*By 1980*	*By 1988*
Acre	152,589	1,165.5	2,464.5	4,626.8	19,500.0	0.8	1.6	3.0	12.8
Amapá	140,276	152.5	170.5	183.7	571.5	0.1	0.1	0.1	0.4
Amazonas	1,567,125	779.5	1,785.8	3,102.2	105,790.0	0.1	0.1	0.2	6.8
Goiás	285,793	3,507.3	10,288.5	11,458.5	33,120.0	1.2	3.6	4.0	11.6
Maranhão	257,451	2,940.8	7,334.0	10,671.1	50,670.0	1.1	2.8	4.1	19.7
Mato Grosso	881.001	10,124.3	28,355.0	53,299.3	208,000.0	1.1	3.2	6.1	23.6
Pará	1,248,042	8,654.0	22,445.3	33,913.8	120,000.0	0.7	0.8	2.7	9.6
Rondônia	243,044	1,216.5	4,184.5	7,579.3	58,000.0	0.3	1.7	3.1	23.7
Roraima	230,104	55.0	143.8	273.1	3,270.0	0.0	0.1	0.1	1.4
Total	5,005,425	28,595.3	77,171.8	125,107.8	598,921.5	0.6	1.5	2.5	12.0

Source: Fearnside (1986b) and World Bank estimates.

in Amazonia Project (RADAM), which employed airborne side-looking radar to gather primary data. These estimates suggested that relatively little clearing of the forest had taken place. Landsat satellite images provided more comprehensive estimates of deforestation a few years later. They indicated that roughly 30,000 square kilometers, or about 0.6 percent of Amazonia (and approximately 1.0 percent of the forest) had been cleared as of 1975 (see table 1). These early Landsat images were cited as proof that the environmentalists—some of whom had predicted the demise of the Amazonian forest by the end of the century—had greatly exaggerated their case (Denevan 1973). More recent data, however, make it clear that there was no cause for complacency.

Landsat images indicate that deforestation has accelerated sharply since the mid-1970s. As shown in table 1, the deforested area increased to 125,000 square kilometers by 1980 and to almost 600,000 square kilometers by 1988. The 1988 figure is equivalent to 12 percent of Amazonia and is larger than France. As in the past, deforestation has been concentrated in certain subregions. In Rondônia and Mato Grosso, for example, nearly one-fourth of the forest has already been cleared, whereas more than 99 percent of the forest is still intact in Amapá. Particularly intense clearing has taken place along the region's major overland routes: the Belém-Brasília highway and its zone of influence in southern Pará and northern Goiás, and the Cuiabá-Pôrto Velho highway and its associated feeder roads in Mato Grosso and Rondônia (Fearnside 1986c and Woodwell, Houghton, and Stone 1986; see also maps 2, 3, and 4).

Proximate Causes of Deforestation

The main proximate causes of deforestation in Amazonia are small-scale agriculture, cattle ranching, logging, road building, hydroelectric development, mining, and urban growth. Unfortunately, the relative contribution of each of these activities cannot be determined with any degree of precision. Its seems clear, however, that the rapid expansion of the agricultural frontier over the past two decades has been the most important single factor. According to agricultural census data, farmland in Amazonia increased from 313,000 square kilometers in 1970 to more than 900,000 square

Table 2. Agricultural Land Use in Legal Amazonia, 1980

Use	*Area (square kilometers)*	*Percentage of area*
Crops		
Annual[a]	42,231.6	5.0
Perennial	7,619.5	0.9
Subtotal	49,851.1	5.9
Pasture	94,098.1	11.1
Undisturbed[b]	704,994.3	83.0
Total	848,943.5	100.0

a. Includes fallow land.

b. Forest, natural pastures, and areas unsuitable for agricultural use (such as rivers, mountains).

Source: IBGE (1983).

kilometers in 1985. This expansion occurred in virtually all of the region's states and territories. Moreover, consistent with the deforestation estimates derived from Landsat images, the census data show that the spread of agriculture was particularly rapid in Rondônia, northern Mato Grosso and Goiás, and southern Pará.

Details on agricultural land use in 1985 have not yet been published. The data in table 2, however, indicate that in 1980 approximately 145,000 square kilometers of Amazonia were used for agricultural purposes, that is, for raising either crops or livestock.[3] Because pasture has clearly been the predominant form of agricultural land use in the region, cattle ranching would appear to be the leading proximate cause of deforestation. Based on comparisons with the 1970 census data, the conversion of forest to pasture occurred at the rate of approximately 8,000–10,000 square kilometers per year during the 1970s. Most, but not all, of this pasture formation took place on large landholdings. In Pará, Mato Grosso, and Goiás—the principal livestock states of Amazonia—70 percent or more of the artificial pasture in 1980 was on farms larger than 1,000 hectares.

---

[3] The 1980 census figure is 20,000 square kilometers larger than the *total* deforested area estimated through Landsat images for the same year (see table 1). This discrepancy probably reflects the conservative bias in the Landsat estimates and the fact that some of the land converted to agricultural uses was not originally forested.

Land devoted to annual cropping, the second most important form of agricultural land use, probably increased by about 2,000 square kilometers per year between 1970 and 1980. This is typically a small-farmer activity. Frequently, however, farm plots devoted to annual crops are sold or abandoned after only a few years of use, owing to rapidly declining yields. These areas are then converted to pasture—often by larger landowners—or are quickly invaded by secondary growth known as *capoeira*. Given this traditional sequence of land use in Amazonia (from undisturbed forest to annual crops to pasture or secondary growth), some of the deforestation attributed to livestock development was probably caused by the spread of small-scale agriculture.

Logging has also grown rapidly in Amazonia over the past two decades. Between 1975 and 1985, for example, regional roundwood production increased from 4.5 million cubic meters per year (14.3 percent of the national total) to 19.8 million (46.2 percent of the national total). It is not clear, however, how much deforestation can be attributed to logging, because much timber extraction in Amazonia is a by-product of land clearing for agricultural purposes. Typically, loggers begin by selectively cutting commercially valuable species in newly opened areas. Such trees usually represent only a very small proportion of the standing forest—as of the late 1970s only five species (out of an estimated 1,500) accounted for 90 percent of the region's timber exports (Browder 1988). The vast majority of the trees have little or no commercial value outside the region and are burned before the planting of crops. Practically no replanting is done, except in the Jari project in northern Pará. In Rondônia, where deforestation has been occurring at an extremely rapid pace in recent years, the 1980 agricultural census shows only 165 hectares planted in trees!

The Evolution of Regional Policies

Government policies designed to open up Amazonia for human settlement and to encourage certain types of economic activity have played a key role in the deforestation process. In particular, massive road-building programs carried out in the 1960s and 1970s made large areas of the region accessible by land for the first time,

Box 1. The Amazonian Rubber Boom

Official interest in Amazonia dates from the colonial period, when the Portuguese Crown exploited the region for its forest products and Indian slave population. The regional economy remained relatively insignificant, however, until the last quarter of the nineteenth century, when the world demand for rubber soared following Charles Goodyear's invention of the vulcanization process in 1839. Owing to its near monopoly on wild rubber in the world's markets, Amazonia enjoyed nearly half a century (roughly from 1870 to 1912) of rapid economic growth. The story of the turn-of-the-century rubber boom illustrates how an activity that is environmentally suited to the rain forest can at the same time be economically unsustainable. It thus provides an interesting counterpoint to the modern regional economy in which some important activities, such as agriculture and cattle ranching, are both environmentally *and* economically unsustainable in most of the rain forest area.

The Amazonian rubber boom brought to the region (if not to all of the region's inhabitants) a level of prosperity that had never even been dreamed of before. To meet the growing demands of North American and European industry, hundreds of thousands of workers were contracted to gather latex in the forest. A new class of "rubber barons" built palatial mansions in the river cities of Manaus and Belém. Prices, which had fluctuated between

and government-sponsored settlement schemes simultaneously attracted migrants from Brazil's Northeast and South regions (see inset on map 3). Special fiscal incentives and subsidized credit lines encouraged land uses such as cattle raising, which allowed a relatively small population to have a large impact on the rain forest.

Operation Amazonia

In 1960, Classic Amazonia (where most of the rain forest is concentrated) had only 2.5 million inhabitants and a per capita income just half the level reached in 1910 at the height of the rubber boom (Santos 1980, also see box 1). When a military government came into power in 1964, Amazonia again gained public attention. In a series of legislative acts and decrees enacted in 1966 and 1967 (cumulatively known as Operation Amazonia), the new government firmly committed itself to the development and occupation of the region, as well as the eventual integration of Amazonia with

$0.75 and $1.50 a pound from 1897 to 1908, rose to more than $3.00 a pound by mid-1910, and rubber challenged coffee for the lead position among Brazil's exports. But, inevitably, the large profits generated by exports of wild rubber attracted the attention of foreign competitors. By the early 1900s the British had established plantations in their Asian colonies that could produce rubber at only one-fourth the cost incurred by Brazilian producers (Resor 1977).

Plantation-grown rubber started entering world markets on a grand scale in late 1910, and by the end of the following year the price of rubber had dropped to $1.00 a pound. The Brazilian government made a futile attempt to save the local rubber interests through the so-called Rubber Defense Plan. Cash premiums were given to persons who planted rubber trees and built rubber processing plants, export taxes on rubber (which were viewed as a major impediment to sales) were drastically reduced, and import taxes on inputs to the rubber industry were abolished. These official attempts to bolster the regional economy did nothing to stanch the ever increasing flow of Asian production, however, and prices plummeted to $0.63 a pound by 1914. For Brazil and Amazonia, the boom was over: between 1910 and 1934 the region's share of the world rubber market fell from 60 percent to 1 percent, and it has remained at insignificant levels ever since (Mahar 1978). The fatal flaw of the government program was in linking the prosperity and future development of Amazonia to the export of one forest product, a product sold on a market in which Brazil could not effectively compete.

the rest of Brazil. These plans included an ambitious road-building program to link Amazonia with the Northeast and South, agricultural colonization schemes, and fiscal incentives to attract new industrial and agricultural enterprises. An administrative structure, which included a regional development agency (Superintendency for the Development of Amazonia, or SUDAM) and a regional development bank (Bank of Amazonia, or BASA), was created to coordinate the implementation of these plans.

The motives behind Operation Amazonia were largely geopolitical. Several neighboring countries (particularly Peru and Venezuela) had already initiated programs to occupy and develop their respective Amazon regions, and Brazil's military leaders were anxious to ensure national sovereignty by establishing self-sustaining settlements in frontier areas. Because vast quantities of natural resources were thought to remain hidden in the forest, this posture is understandable. But little thought was given to the need for an economic development strategy that would be responsive to the unique physical and human environments of Amazonia. The first model adopted, which emphasized import substitution and industrialization, was lifted virtually unaltered from the country's Northeast, a region different in almost every respect from Amazonia.

The Belém-Brasília Highway

In 1960, Classic Amazonia had only 6,000 kilometers of roads, less than 300 kilometers of which were paved. Except by air and long sea routes, the region was virtually cut off from the rest of Brazil. Intraregional travel was also difficult, and the sparse populations tended to cluster in the region's two major cities, Belém and Manaus, and in small towns and villages scattered along the Amazon River and its 1,100 tributaries. Although this centuries-old isolation from the more dynamic South had arguably retarded the region's economic development, it had also protected the rain forest from destruction. The physical isolation of Amazonia—and the protection this provided to the rain forest—came to an end in 1964 with the completion of a 1,900-kilometer all-weather highway that connected the new capital city of Brasília in Brazil's heartland with Belém at the mouth of the Amazon River.

Large numbers of migrants in search of land and employment entered the region via the Belém-Brasília highway (BR-010). So did firms that wanted to establish cattle ranches to take advantage of the cheap land and generous tax and credit incentives offered by the government. Official estimates suggest that the total human population in the zone of influence of the highway (which includes some areas outside Amazonia) increased from 100,000 in 1960 to about 2 million ten years later (Resende 1973, p. 20). The same source estimates that the cattle population increased from practically nothing to 5 million during the decade. To be sure, these official estimates exaggerate both the size and growth rate of the human and cattle populations. M. T. Katzman (1977), for example, estimates that the road attracted at most 320,000 new settlers between 1960 and 1970. Nevertheless, there can be no doubt that the surge of migration and economic activity stimulated by the Belém-Brasília highway contributed to widespread deforestation. One traveler around 1970, who noted the devastation and apparent abandonment of the land on either side of the highway, described the area around Paragominas in eastern Pará (the site of numerous SUDAM-approved cattle ranches) as a "ghost landscape" (Paula 1971).

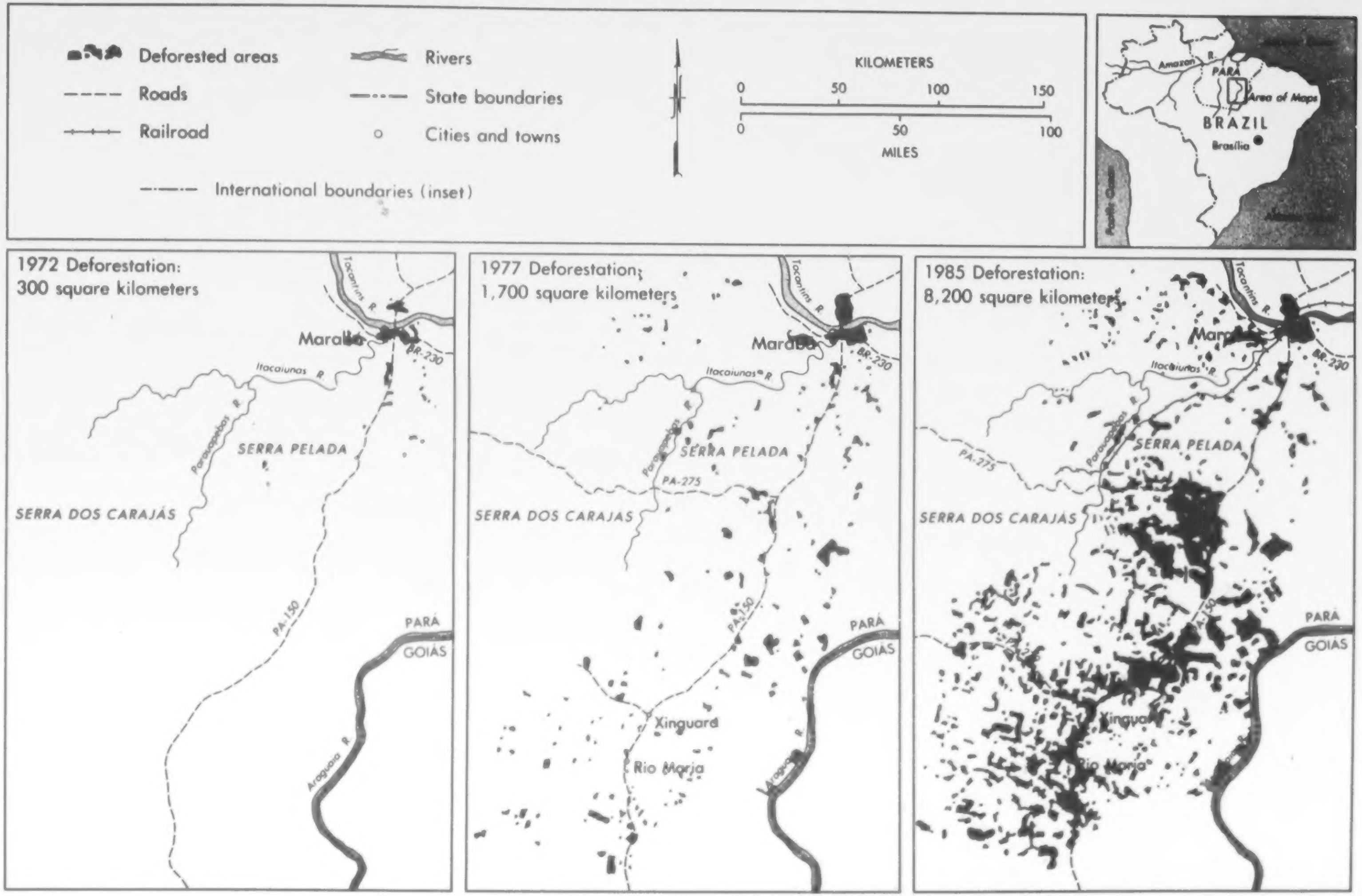
Environmental degradation was not confined to areas adjacent to the Belém-Brasília highway. The increase in population associated with the completion of the main highway quickly generated demand for secondary and feeder roads, which in turn attracted more population. Landsat photos vividly illustrate the impact on the rain forest of one such highway (PA-150) in southern Pará that was opened to traffic in the late 1960s. Within one 47,000-square-kilometer area (small by Amazonian standards, but about the size of Switzerland) traversed by this road, the cleared area jumped from 300 square kilometers in 1972 (0.6 percent of the area), to 1,700 in 1977 (3.6 percent), to 8,200 (17.3 percent) in 1985 (see map 2). Although the relative contribution of different activities to this deforestation is uncertain, the conversion of forest to pasture has undoubtedly been a leading cause.

Incentives for Livestock Development

As already noted, a key objective of Operation Amazonia was to attract private enterprise to the region. This was to be achieved through increased public expenditures on infrastructure—for example, roads, airports, telecommunications—and special fiscal incentives and credit lines for firms willing to establish operations in Amazonia. The package of fiscal benefits available to qualifying firms was extensive and included holidays from the corporate income tax for ten to fifteen years, as well as exemptions from export taxes and import duties. Additional fiscal incentives were extended in 1967 to firms locating in western Amazonia to compensate for that subregion's alleged disadvantages, such as the long distance to major markets, an inadequate supply of local labor, and the lack of necessary infrastructure (Mahar 1976).

INVESTMENT TAX CREDITS. The most powerful of the incentives allowed registered Brazilian corporations to take up to a 50 percent credit against their federal income tax liabilities if the resulting

Map 2. Deforestation in Southeast Pará, 1972, 1977, and 1985


Deforested areas
Roads
Railroad
Rivers
State boundaries
Cities and towns
International boundaries (inset)
KILOMETERS
0
50
100
150
0
50
100
MILES
Amazon R.
PARÁ
Area of Maps
BRAZIL
Brasília
1972 Deforestation:
300 square kilometers
1977 Deforestation:
1,700 square kilometers
1985 Deforestation:
8,200 square kilometers
Tocantins R.
Marabá
BR-230
Itacaiunas R.
Parauapebas R.
SERRA PELADA
SERRA DOS CARAJÁS
PA-275
PA-150
Xinguara
Rio Maria
Araguaia R.
PARÁ
GOIÁS

savings were invested in projects located in Amazonia and approved by SUDAM. Investment projects could be new enterprises or simply the expansion or modernization of existing ones. Under the 1963 legislation which created the investment tax credit, only industrial projects were eligible; in 1966 eligibility was expanded to include projects in the agricultural, livestock, and service sectors.[4] Depending on the priority assigned to a given project by SUDAM, tax credit funds could constitute up to 75 percent of investment. Although the criteria used in selecting and ranking projects have changed several times over the years, rankings have tended to be positively related to the following factors: use of regional inputs, employment generation, level of technology, contribution to the balance of payments, and location in priority areas. Since 1979 the approval of livestock projects in areas of rain forest (*floresta densa*) has been officially prohibited, but this rule has been difficult to enforce.

The tax credit mechanism proved very attractive to investors, and by late 1985 about 950 projects had been approved by SUDAM. Of this total, 631 projects were in the livestock sector (Garcia Gasques and Yokomizo 1986, p. 51). SUDAM-approved livestock projects have now been established in all parts of Amazonia, although about three-fourths are located in southern Pará and northern Mato Grosso. These projects have probably been the single most important source of deforestation in these two subregions. Their relative contribution to deforestation in Amazonia as a whole, however, has clearly been much smaller—probably less than 10 percent of the total.

The size of the SUDAM-approved cattle ranches is large by any standard. The ranches currently cover 8.4 million hectares and average about 24,000 hectares each. (In contrast, the average farm in Amazonia in 1985 comprised only 90 hectares.) Several ranches are larger than 100,000 hectares. The Suia-Missu ranch in northern Mato Grosso, the largest of the group, covers 560,000 hectares (Branford and Glock 1985, p. 109). Despite their size, these ranches generate relatively little employment, except during the initial stage of felling and burning the forest. At full development, these ranches typically employ only one person for every 250–300 hectares of pasture (Garcia Gasques and Yokomizo 1986, p. 77). In areas of Amazonia with peasant economies based on extractive activities, the conversion of forest to pasture has actually had negative employment effects. The felling of stands of Brazil nut trees around Santarém in Pará, for example, deprived the surrounding peasant communities of employment and income (Bunker 1981). The former Brazil nut gatherers migrated to nearby towns, where they now depend on temporary employment on the cattle ranches. Ranchers had selected these areas for pasture formation because they were the only *terra firme* lands with titles which could be used as guarantees for bank credit.

---

[4] The tax credit mechanism was further modified in 1974. The new legislation, which applies currently, allowed firms only a 25 percent credit against their income tax liability. It also called for the establishment of the Amazon Investment Fund (FINAM), a type of mutual fund managed by BASA. Today, firms taking advantage of the tax credit initially receive shares in FINAM. The fund, in turn, acquires shares of stock in firms carrying out projects approved by SUDAM. Investors may hold or sell their shares in the fund or trade them for corporate stock held by FINAM. Investors with their own projects may directly acquire shares of their own stock. All corporate stock acquired from the FINAM portfolio is nonnegotiable for four years (for details, see BASA 1981).

Over the years, livestock projects have absorbed about 44 percent of the tax credit funds administered by SUDAM. In absolute terms total disbursements to the owners of these projects have amounted to the equivalent of approximately US$700 million (Browder 1988). Despite this huge subsidy, only ninety-two livestock projects have been awarded certificates of completion by SUDAM. Moreover, most of the completed projects have performed far below expectations. A field survey by the Institute of Economic and Social Planning (IPEA) found that the average level of production in a sample of nine such projects was less than 16 percent of that originally projected; three of the nine projects visited were not producing anything (Garcia Gasques and Yokomizo 1986, p. 56). Data gathered by the IPEA on twenty-six livestock projects still under implementation provide little basis for optimism that performance levels will improve in the future. Average production levels of projects in this group (all of which have been under implementation for at least seven years) are running at only 9 percent of projections; twelve projects (with an average of sixteen years under implementation) were found to have no marketed output whatsoever.

Table 3. Internal Rates of Return to a Typical SUDAM-Approved Livestock Project under Two Scenarios
(percent)

	Increase in land value		
Scenario	*0 percent*	*15 percent*	*30 percent*
High cattle prices			
Appropriate grazing intensity			
Corporation resources	16	18	24
All resources	−1	2	9
Overgrazing			
Corporation resources	23	24	27
All resources	−2	0	4
Low cattle prices			
Appropriate grazing intensity			
Corporation resources	−3	6	17
All resources	−14	−6	5
Overgrazing			
Corporation resources	16	18	23
All resources	−10	−7	−1

Notes: Low input prices are assumed in both scenarios. Data for corporation resources ignore capital expenditures financed through fiscal incentives and official credit. Data for all resources treat fiscal incentives and official credit as if they were the corporation's own capital.

Source: Adapted from Hecht, Norgaard, and Possio (n.d.).

The IPEA study attributes the poor performance of SUDAM-approved livestock projects largely to administrative and management problems such as inadequate purchases of breeding stock, frequent changes in project ownership, delays in the release of fiscal incentive funds, cost escalation, and weak supervision on the part of SUDAM. Surely these problems constitute part of the explanation. A recent study, however, argues convincingly that cattle ranching under conditions commonly prevailing in Amazonia is *intrinsically* uneconomic (Hecht, Norgaard, and Possio n.d.).

Using a simulation model for a typical 20,000-hectare cattle ranch for which 75 percent of investment is provided by tax credit funds, the authors calculated internal rates of return (IRRS), to both the investor's own resources ("fresh money") and all resources, under various assumptions regarding technology employed, intensity of grazing, and rates of land appreciation. The results under two scenarios are summarized in table 3. They show that livestock activities in Amazonia are profitable to corporations *only* when official subsidies or capital gains from land appreciation are present, and that the IRR to a ranching corporation's own resources can be improved substantially through overgrazing. Indeed, when cattle prices are low and land values have not appreciated, cattle ranching can be made profitable only through overgrazing. Overgrazing, however, degrades the pasture and ultimately undermines the long-term viability of the ranch. Although it is technically possible to recuperate degraded pastures, the continued availability of tax credit funds for land clearing, road and fence building, and pasture development makes it more profitable for a corporation to form new pastures than to maintain existing ones.

The findings of the simulation exercise described above have been largely confirmed by field observations. On the environmental issue, Goodland (1980, p. 18) rates cattle ranching as "the worst . . . of all conceivable alternatives" for Amazonia on the basis of its high potential for degrading the soil. Although some researchers debate this point, a comprehensive soil survey (involving eighty samples per age class of pasture) carried out in major cattle areas in eastern Amazonia lends it strong support. The survey indicates that changes in soil chemistry following the conversion of forest to pasture are "relatively neutral for N and K, negative for P and C, and mildly positive for Ca, Mg and pH" (Hecht 1985, p. 677). In other words, the clearing of forest renders the potential of the soil low to marginal for pasture formation, especially if physical changes in the soil (particularly compaction) and the invasion of weeds are also considered. In practical terms this means that stocking rates, which may be maintained at 1.00 animal per hectare during the initial years of pasture formation, typically decline to 0.25 animal per hectare after the fifth year.

The IPEA field survey found few ranch owners who were seriously interested in developing sustainable beef production and confirmed that many projects were being exploited solely for their fiscal benefits. In visits to projects in southern Pará, the IPEA team discovered that persons with five or six projects approved by SUDAM had received tax credit funds without ever having initiated project implementation. After the tax credit funds had been fully disbursed, these projects were either sold or abandoned (Garcia

Gasques and Yokomizo 1986, p. 67). In other cases, entrepreneurs intentionally delayed project implementation in order to obtain additional tax credit funds from SUDAM through successive project "reformulations." Changes in project ownership were found to be very frequent among the livestock projects in the sample survey; some had been sold up to six times since their approval by SUDAM. Because a transfer of ownership also transfers the right to receive tax credit funds, the IPEA team inferred from the high frequency of sales that many purchasers were primarily interested in the official subsidies, not in beef production.

Investors interested in land appreciation have also used the legitimacy conferred by a SUDAM-approved project to control huge tracts of land. According to the IPEA study, one group in southern Pará controls a 330,000-hectare parcel on which five projects have been approved for fiscal incentives. Effective control over land is particularly important in Amazonia, where legal rights are vague and squatting by migrants is common. To discourage migrants from settling on his land, one rancher visited by the IPEA team had rented plots along the borders of his property to small farmers. Other ranchers have employed more violent means to keep prospective settlers off their land (Branford and Glock 1985). Although data on the returns from land speculation in Amazonia are not available, anecdotal evidence suggests that huge fortunes have been made, especially by those who entered the market in the 1960s (Branford and Glock 1985, pp. 49–51). But even relative latecomers could have done well. For example, investors who purchased average pastureland in Pará in 1977 could have sold it ten years later for a respectable real gain of almost 100 percent on their initial outlay even if they had produced nothing during the intervening period (FGV/CEA 1985 and unpublished data).

The environmental damage associated with cattle ranching (including operations not benefiting from fiscal incentives) may account for as much as two-thirds of the deforestation in the region (see table 2) and has not gone unnoticed by government authorities. The Parliamentary Commission on the Devastation of Amazonia and Its Implications, for example, frequently cited the role of the SUDAM-approved livestock projects during its proceedings in 1978–79 (Brazil 1978). An effort to halt further deforestation was mounted in 1979, when SUDAM officially declared its intention not to approve any new livestock projects in rain forest areas. To implement this policy, SUDAM used satellite images as part of the project evaluation process in 1979–80. According to the IPEA study, however, "this practice was abandoned and projects approved without it" in subsequent years (Garcia Gasques and Yokomizo 1986, p. 80).

SUBSIDIZED CREDIT. Although livestock ranches benefiting from SUDAM-administered fiscal incentives have been major contributors to the deforestation in southern Pará and northern Mato Grosso, they have not played a dominant role in the deforestation elsewhere in the region. Probably 90 percent of all pasture formation in Amazonia to date has been carried out by firms or individuals who have not received fiscal incentive funds. Clearly, other factors have played a role. One possibility frequently mentioned in the literature is the availability of subsidized rural credit (Browder 1988 and Ledec 1985). Subsidized credit lines, like the fiscal incentive funds, increase private rates of return to investment and thereby encourage activities—and by extension, deforestation—which would not be undertaken if credit were priced at market rates.

Subsidized rural credit has long been used by the Brazilian government as a way to compensate agriculture for foreign exchange overvaluation, import controls, and other pro-industry macroeconomic policies. After 1974, however, in the wake of government efforts to stimulate the economy following the first oil crisis, the volume of subsidized rural credit increased dramatically. This increase in volume was accompanied by a larger unit subsidy. By the end of the 1970s, official rural credit was available at an average rate of −40 percent (Knight and others 1984, p. 61). Although farmers and ranchers in Amazonia continued to be allocated only a small proportion of this credit (less than 2 percent of the national total), they fully participated in the growth in its volume. Agricultural interests in Amazonia were also provided access to special credit lines reserved for Brazil's underdeveloped regions.

As shown in table 4, the volume of subsidized rural credit com-

Table 4. Commitments of Official Rural Credit in Classic Amazonia, 1970–85

	Total	Crops		Livestock	
Year	*Millions of 1985 cruzados*	*Millions of 1985 cruzados*	*Percentage of total*	*Millions of 1985 cruzados*	*Percentage of total*
1970	106.0	78.2	73.8	27.8	26.2
1971	153.3	102.3	66.7	51.0	33.3
1972	264.2	157.2	59.5	107.0	40.5
1973	306.7	168.4	54.9	138.3	45.1
1974	203.9	118.7	58.2	85.2	41.8
1975	495.4	297.2	60.0	198.2	40.0
1976	899.5	417.4	46.4	482.1	53.6
1977	985.7	620.0	62.9	365.7	37.1
1978	1,332.0	901.8	67.7	430.2	32.3
1979	1,824.9	1,419.8	77.8	405.1	22.2
1980	1,882.6	1,724.5	91.6	158.1	8.4
1981	1,285.7	1,135.3	88.3	150.4	11.7
1982	870.5	637.2	73.2	233.3	26.8
1983	472.8	411.3	87.0	61.5	13.0
1984	198.2	175.4	88.5	22.8	11.5
1985	296.9	259.5	87.4	37.4	12.6

Source: IBGE (various years).

mitted to Classic Amazonia increased almost tenfold in real terms between 1974 and 1980. In almost all years the bulk of this credit was allocated to crop production. But the livestock sector also received large increases in subsidized credit after 1974. Much of this credit was extended through special lines with particularly attractive terms. For example, under a regional development program known as the Program of Agricultural, Livestock, and Mineral Poles in Amazonia, or POLAMAZONIA, twenty-year investment credit was made available to ranchers at a nominal annual rate of 12 percent. The National Program of Livestock Development (PROPEC), which provided credit to ranchers in Brazil's more developed South and Southeast at a nominal rate of 45 percent per year, offered terms similar to those of POLAMAZONIA to ranchers located in the Amazon region.

The effects of subsidized credit on the behavior of farmers and ranchers in Amazonia are difficult to quantify for several reasons. First, data about the farms and ranches—such as size of operation, area cleared, output, and productivity—are extremely limited.

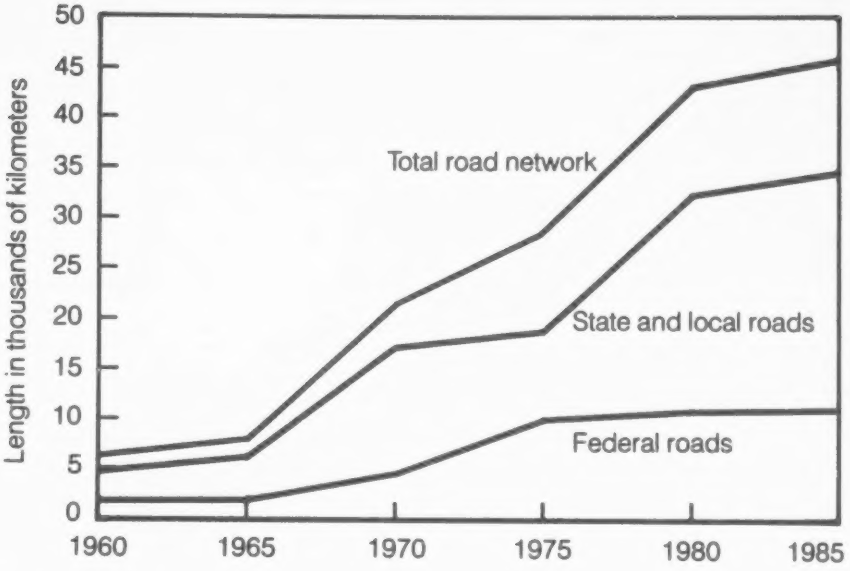
Second, a significant part of subsidized credit directed to agriculture and livestock was probably diverted to other uses. Although little is known about the extent of credit diversion in Amazonia, World Bank analysts estimated it to be on the order of 20–30 percent of total rural credit in the late 1970s (Knight and others 1984, p. 49). Finally, the influence of interest rate subsidies is inextricably mixed with that of the macroeconomic and sectoral policies they were supposed to offset.

Despite these caveats, certain general conclusions are clear. The availability of subsidized rural credit undoubtedly facilitated the acquisition and deforestation of large tracts of land in Amazonia, particularly during the latter half of the 1970s. (How much less deforestation would have occurred in the absence of subsidized credit is unknown, however.) Moreover, the special credit lines which increased the unit subsidy element specifically for undertakings in Amazonia as opposed to the more developed regions of Brazil probably attracted some resources which would have otherwise been invested in farms and ranches in the less fragile natural environments of the South and Southeast.

In addition to its negative environmental effects, subsidized credit clearly served to skew further the distribution of wealth in the region. Because the possession of a land title is normally a prerequisite for obtaining investment credit in Brazil, Amazonia's many sharecroppers, tenants, and squatters in particular were effectively denied access to a large part of the subsidy. Moreover, those persons without access to credit were obliged to bear a disproportionate share of the costs—for example, high input prices and low output prices—of the policies subsidized credit was supposed to offset. Subsidized credit also reduced the chances of the landless to obtain titles, by raising average land prices well above what could be earned from the land through farming or ranching. Regressions based on data for six states (only one of which, Mato Grosso, is included in Amazonia) indicate that 67 percent of the change in rural land prices in 1969–76 can be explained by the intensity of credit use (Knight and others 1984, pp. 80–81).

Since 1980 the volume of official rural credit has been drastically reduced in an effort to restore internal balance to the Brazilian economy (table 4). Moreover, the subsidy element in this credit

Figure 1. Amazonian Road Network, 1960–85

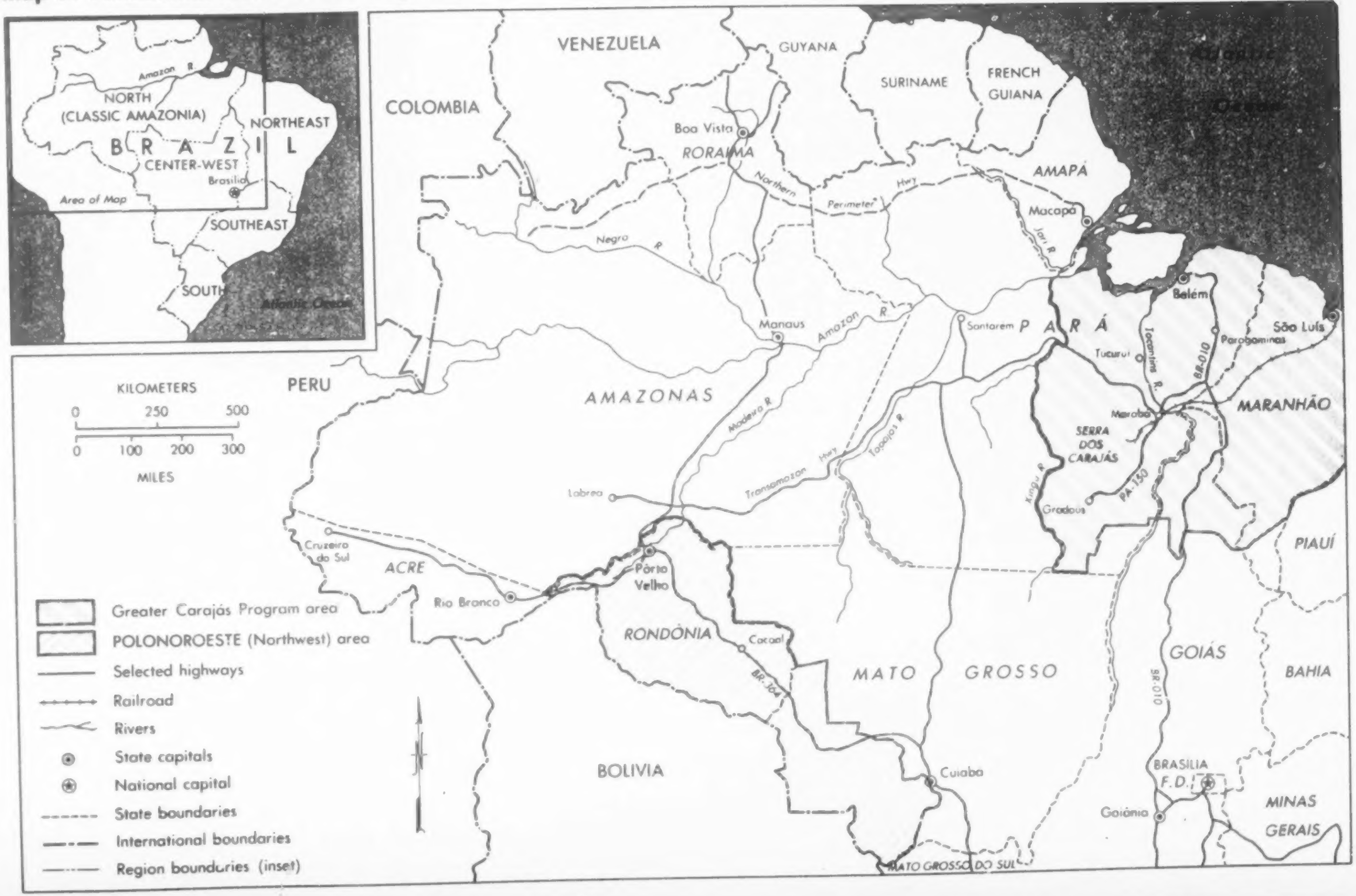


was eliminated completely in mid-1987. If sustained, this most welcome reversal of the government's long-standing policy on rural credit will surely have beneficial macroeconomic, sectoral, and environmental effects. The abrupt decline in the volume of subsidized credit in Amazonia has, however, disrupted some small- and medium-scale agriculture in the region. This disruption may ironically have some negative environmental effects in the short run. Some farmers in Rondônia who had been advised by extension agents to plant tree crops now find themselves unable to afford the necessary fertilizers, herbicides, and other inputs. Many have therefore reverted to activities that are more damaging to the environment such as slash-and-burn agriculture and extensive livestock raising.

The National Integration Program

As shown in figure 1, the road-building boom begun in the late 1960s continued into the 1970s. Considerable impetus to this construction was provided by the National Integration Program (PIN), which was established in 1970 and financed through a 30 percent share of the fiscal incentive funds. (A companion program, the

Map 3. Amazonia: Main Federal Highways


Amazon R.
NORTH
(CLASSIC AMAZONIA)
NORTHEAST
B R A Z I L
CENTER-WEST
Brasília
Area of Map
SOUTHEAST
SOUTH
Atlantic Ocean
VENEZUELA
GUYANA
SURINAME
FRENCH
GUIANA
COLOMBIA
Boa Vista
RORAIMA
Northern
Perimeter
Hwy
AMAPÁ
Macapá
Jari R.
Negro R.
Manaus
Amazon R.
Santarem
P A R Á
Belém
São Luís
Paragominas
Tucuruí
Tocantins R.
BR-010
MARANHÃO
Marabá
SERRA
DOS
CARAJÁS
Xingu R.
Gradaus
PA-150
PERU
AMAZONAS
Madeira R.
Tapajos R.
Transamazon
Hwy
Labrea
Cruzeiro
do Sul
ACRE
Pôrto
Velho
Rio Branco
RONDÔNIA
Cacoal
BR-364
MATO GROSSO
PIAUÍ
GOIÁS
BAHIA
BR-010
BOLIVIA
Cuiabá
BRASILIA
F.D.
Goiânia
MINAS
GERAIS
MATO GROSSO DO SUL
KILOMETERS
0
250
500
0
100
200
300
MILES
Greater Carajás Program area
POLONOROESTE (Northwest) area
Selected highways
Railroad
Rivers
State capitals
National capital
State boundaries
International boundaries
Region boundaries (inset)

Land Redistribution Program, or PROTERRA, absorbed an additional 20 percent of these funds.) Through PIN, resources were made available for the construction of some 15,000 kilometers of roads, including an east-west (Transamazon) highway connecting Amazonia with the Northeast and a north-south (Cuiabá-Santarém) highway linking it with the South and Southeast (map 3). Plans were also made to build a second east-west highway (Northern Perimeter) along the northern bank of the Amazon River. A 20-kilometer strip of land was to be reserved on either side of these highways for agricultural settlement projects. In addition to providing funds for road construction and settlement in Amazonia, PIN was to finance the irrigation of 40,000 hectares in the Northeast.

Most accounts hold that the decision to establish PIN resulted from President Emílio Garrastazú Médici's visit in 1970 to the chronically poor Northeast to observe the effects of a particularly severe drought. The construction of an east-west highway, it was reasoned, would provide a short-term solution to the drought problem by creating jobs for displaced Northeastern families. In the longer term, government-sponsored settlements along the Transamazon highway were expected to alleviate population and social pressures in the Northeast and at the same time promote the effective occupation of Amazonia. Another motive for PIN was the hope that valuable mineral deposits would be uncovered during road construction. The overriding motive, however, was national security and the fear of foreign domination in the region. In the late 1960s such xenophobia intensified amid publicity given to a quixotic scheme by the U.S.-based Hudson Institute to create a series of "Great Lakes" by damming the Amazon River as well as revelations that large tracts of land in the region had been sold to foreigners.

The first concrete result of PIN was the completion of the initial 1,200-kilometer stretch of the Transamazon highway in late 1972.[5] The government hoped to settle some of the Northeast's "excess" rural population alongside this part of the highway, which intersects both the Belém-Brasília and Cuiabá-Santarém highways. Plans called for settling 70,000 families between 1972 and 1974 (Mahar 1979). To carry out the settlement program, the National Institute for Colonization and Agrarian Reform, or INCRA (now known as the Ministry of Agrarian Reform and Development, or MIRAD) established a network of new villages, towns, and cities at predetermined locations along the highway and demarcated 100-hectare farm lots nearby. The government actively recruited colonists in both the South and the Northeast using massive propaganda campaigns that promised attractive benefit packages. The benefits included temporary household subsidies averaging the equivalent of US$30 a month for six to eight months, guaranteed crop financing, and twenty-year loans on generous terms for purchases of farm plots and housing (Smith 1982 and Moran 1981).

---

[5] An additional 1,000-kilometer stretch of the Transamazon was inaugurated in early 1974. The 1,800-kilometer Cuiabá-Santarém highway was completed in late 1976. Construction of the 2,500-kilometer Northern Perimeter highway was essentially abandoned in the late 1970s for financial and technical reasons.

Despite the huge amount of human and financial resources expended, the accomplishments of the PIN-financed road-building and directed settlement program were extremely modest. By the end of 1974 only about 5,700 families had been effectively settled along the Transamazon highway, less than 10 percent of the target set by the government (Moran 1981). By the end of the decade the total had risen to only 8,000 families, and just 40 percent of these had come from the Northeast. The demographic data point up the failure of the Transamazon settlement scheme to act as a safety valve for social pressures in the Northeast: the approximately 23,000 Northeasterners accommodated in the settlement areas during the 1970s represented less than 1 percent of the Northeast's population growth (6 million) during the period (Smith 1981). Hopes that new natural resources would be uncovered during highway construction were also shattered. No sizable mineral deposits were discovered; as of the early 1980s only one company was reported to be extracting minerals (tin ore) along the Transamazon highway (Smith 1981).

The directed settlement schemes of the early and mid-1970s failed to create self-sustaining agricultural communities for several reasons. Certainly, adverse environmental factors played a large role. Both the routing of the Transamazon highway and the layout of the colonization projects were done hastily and with little regard for soil fertility or topography. Only about 3 percent of the soils in the area of the highway can be classified as naturally fertile, and most of the area is hilly; extremes of relief from trough to hillcrest attain 40 meters within 0.5 kilometer in some areas (Smith 1981). As a result of these factors, cleared land eroded rapidly, which necessitated expensive maintenance work on the highway and the burning of additional forest to restore lost soil fertility. The alteration of the forest also created favorable breeding conditions for the *Anopheles* mosquito, the most common vector of malaria. During the early 1970s the rate of infection among the inhabitants in towns along the Transamazon was on the order of 20 percent (Moran 1981). Since the peak transmission periods for malaria coincide with the planting and harvesting seasons in the main settlement areas, it is likely that this debilitating disease significantly reduced agricultural yields on many farms (Smith 1982).

Institutional factors also played a role. Government planners and extension workers based the agricultural development of the settlement areas on annual crops, particularly upland rice, which are generally considered to be environmentally and economically unsustainable in areas cleared from tropical rain forests, except under very favorable circumstances (Fearnside 1983 and Goodland 1980). By and large, the Transamazon settlers found circumstances that were anything but favorable. First, the colonization projects were far away from major markets for agricultural commodities; this put settlers at a further disadvantage compared with more efficient producers elsewhere in Brazil. Second, largely because of the high cost of transport, fertilizers, pesticides, and herbicides were sold in the region at prices beyond the reach of most small producers. Without these modern inputs, crops often succumbed to pests and diseases; and virtually the only way for farmers to maintain average yields was to fell and burn more forest. Finally, the frequent long trips to town and bureaucratic red tape required by the official banking system discouraged farmers from seeking rural credit. Moreover, it is reported that the Bank of Brazil provided more generous loans to farmers growing crops on land converted from mature forest because the yields tended to be higher in such areas than in areas converted from secondary growth (Smith 1981). This practice, of course, encouraged further clearing of the forest.

Ironically, the failure of the PIN-financed road-building and settlement schemes to attract many migrants or to stimulate much economic activity had a beneficial effect on the environment. Substantial deforestation did occur, but it was concentrated around the settlement areas of central Pará. According to one estimate, only about 4 percent of the deforested area in Amazonia in the early 1980s can be directly attributed to Transamazon settlers (Browder 1988). Deforestation along the western reaches of the Transamazon highway in Amazonas has been minor. Several other roads built during the 1970s—Cuiabá-Santarém, Pôrto Velho-Manaus, and Northern Perimeter—have also had limited environmental impacts.

An important difference between the highways built by PIN in the 1970s and those built in the 1960s (Belém-Brasília and Cuiabá-Pôrto Velho) is that the earlier routes effectively linked the frontier with the country's urban and industrial centers. According to one author, the ease of movement of commodities to and from these centers is "what counts most with regard to effects on settlement" and, by extension, on the environment (Sawyer 1984). That no important mineral deposits or areas of fertile soils were discovered along the PIN-financed highways also helped to protect the rain forest.

The Cuiabá-Pôrto Velho Highway and POLONOROESTE

In 1968, just a few years after the completion of the Belém-Brasília highway, the construction of another road—the 1,500-kilometer Cuiabá-Pôrto Velho highway (BR-364)—opened up the 243,000-square-kilometer state (then a federal territory) of Rondônia for settlement. This part of western Amazonia, which had been a rich rubber-producing area in the boom years at the turn of the century, became an important source of cassiterite (tin) and gold in the mid-1950s. Until the latter half of the 1960s, however, Rondônia, like most other parts of Amazonia, was virtually inaccessible by land. To reach the southern part of the country one first had to journey northeast for several weeks, by boat and ship on the Madeira and Amazon rivers. In 1960, Rondônia's population (mostly itinerant rubber tappers and prospectors) numbered only 70,000, and practically all of the rain forest, which covered about 80 percent of the state, was still intact.

As in the case of the Belém-Brasília highway, the completion of BR–364 was followed by a wave of migration. The migratory flow to Rondônia, which had averaged perhaps 3,000 per year in the 1960s, increased tenfold in the ensuing decade (IBGE 1979; Mahar and others 1981) as migrants, land grabbers (*grileiros*), and adventurers flocked to the area seeking plots of fertile land that were purportedly free for the asking.[6] At the same time, the regional makeup of the newcomers changed. Whereas the vast majority of Rondônia's original settlers had come from the North and Northeast, most of the new contingent were experienced small-scale farmers from the southern state of Paraná. Large numbers also came from Mato Grosso, Minas Gerais, Espírito Santo, and São Paulo.

Both "pull" and "push" factors explain the sharp increase in migration to Rondônia after 1970. Two pull factors have predominated. First, the Cuiabá–Pôrto Velho highway happened to traverse a few areas with relatively fertile soil, a fact that was publicized (and exaggerated) both by the government and by early settlers in their letters to family and friends. Second, 100-hectare lots, along with basic services and infrastructure, could be obtained at a nominal price in several agricultural colonization projects in Rondônia. The most important push factor has been the drastic reduction in employment opportunities in the South and Southeast brought on by fundamental changes in the rural economy of those regions, including the rapid spread of a mechanized system of soybean production, killing frosts in coffee-growing areas, and the fragmentation of landholdings (see box 2).

Most of the migrants hoped to settle in one of the seven colonization projects that INCRA established on 2.7 million hectares between 1970 and 1975. In contrast to the its role in the settlement of areas along the Transamazon highway, INCRA did not actively recruit settlers for Rondônia; its mandate was to provide lots, roads, and other basic infrastructure for a population that had moved to the region spontaneously. As the size and speed of the

---

[6] About 10 percent of Rondônia's soils are considered to be of good quality; this appears to be considerably better than the average for Amazonia as a whole (Mahar and others 1981, p. 58).

Box 2. The Rondônia-Paraná Connection

The mid-1960s signaled the beginning of a rapid modernization of Brazil's agricultural sector, a process which had profound effects on the structure of production, landownership, employment, and the volume and direction of internal migration. To a large extent this modernization was induced by government policies that expanded the volume of subsidized credit for the purchase of improved seeds, farm implements, fertilizers, pesticides, and insecticides. Agricultural modernization was also encouraged by an expansion and redirection of the country's research and extension services. Strong international markets for primary commodities provided additional impetus. Although agricultural modernization has now spread throughout much of Brazil, some of the earliest and most profound effects of this process were felt in the southern state of Paraná.

In the late 1920s the northern part of Paraná constituted Brazil's agricultural frontier. To promote settlement of this area, the state government sold about 12,000 square kilometers to a British company—Paraná Plantations Limited—for subsequent resale to prospective settlers in small and medium-size lots (Margolis 1973). By the 1940s and 1950s this colonization effort had achieved its goal of establishing a prosperous and egalitarian (by Brazilian standards) rural society that was based on the production of coffee and food crops such as maize, rice, and beans. In fact, by the 1959–60 harvest, Paraná had surpassed São Paulo as Brazil's top coffee-producing state. Shortly thereafter, however, a series of problems, including soil depletion, plant diseases, overproduction, and lowered producer prices, precipitated an abrupt decline in the region's coffee-based economy. The national government accelerated this decline in the mid-1960s by financing a coffee eradication program that allowed farmers to be paid for cutting down their coffee trees. Under this program more than 400 million coffee trees were eliminated in Paraná between 1961 and 1969 (Oliveira 1978).

Although the government encouraged new coffee plantings during the early 1970s, the structure of Paraná's rural economy was irrevocably altered. The state's coffee economy was largely unsuited for the agricultural mechanization then being promoted through increasing volumes of subsidized

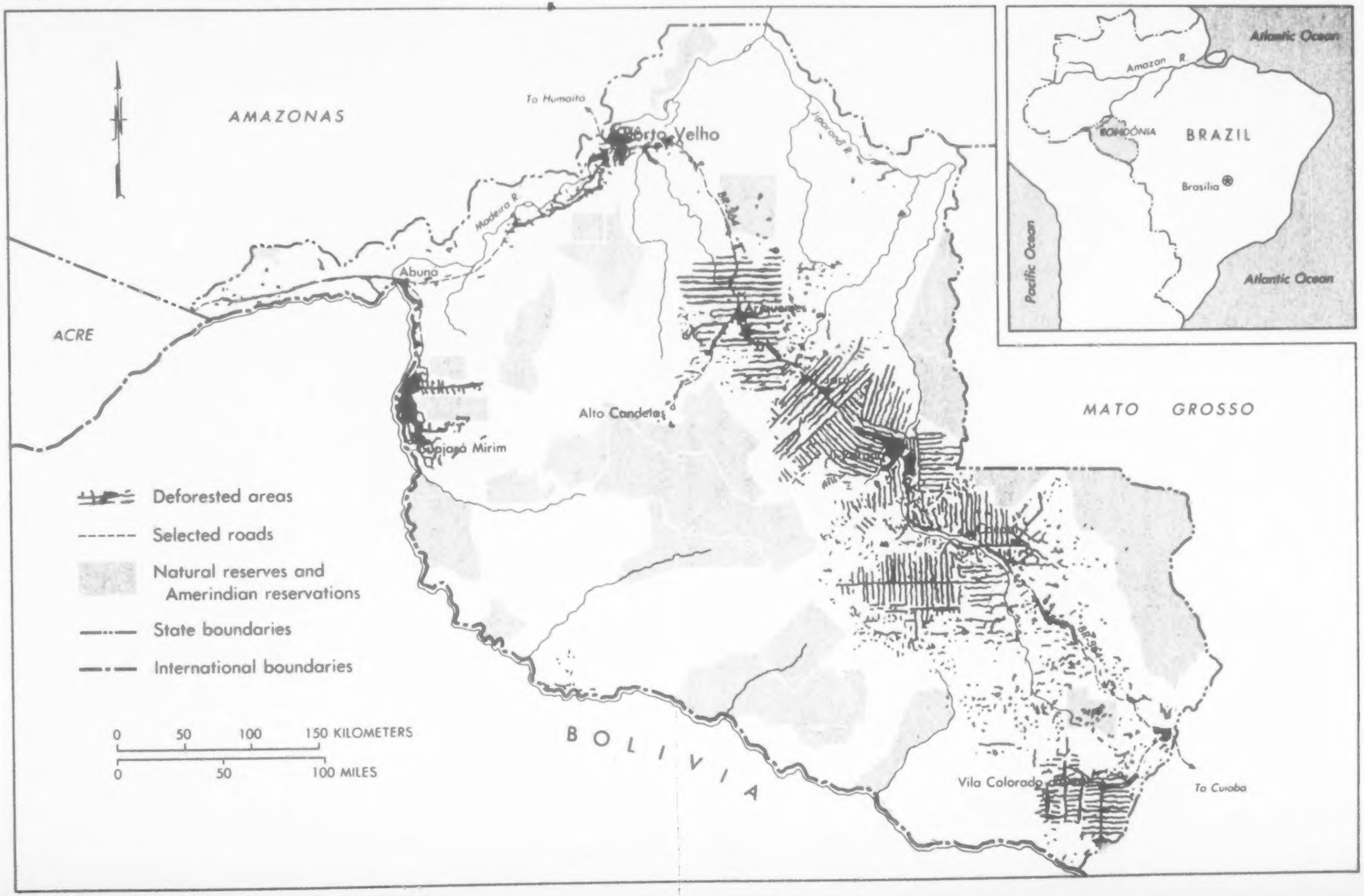
migratory flow increased, however, the demand for space in official projects quickly exceeded the supply.

By 1977, INCRA had settled about 28,000 families; an additional 30,000 agricultural families had joined the marginal population of the newly created urban areas while they awaited their lots, sometimes for as long as two years (Martine 1980, pp. 89–90). Many others became sharecroppers on the land of established colonists credit and was further devastated by a major frost in 1975. Many former coffee-growing areas were converted to a mechanized system of soybean cultivation that required larger farms and fewer labor inputs. Data on land distribution and use give some idea of the extent of this transformation. Between 1970 and 1980 the number of farms smaller than 50 hectares fell by 109,000 units, a combined loss of 890,000 hectares in this category; in contrast, farms larger than 1,000 hectares increased by 450 units, a gain of more than 1.0 million hectares (Carnasciali and others 1987). During this same period the land area devoted to coffee production fell from 1.2 million hectares to 630,000, and the land in soybeans rose from 172,000 hectares to 2.3 million. Many agricultural laborers, especially sharecroppers and tenants, lost their only source of income in the process. As a result, net migration out of the rural areas of Paraná reached 2.5 million in the 1970s compared with a net gain of some 170,000 in the previous decade (Martine 1988).

Labor released through the process of agricultural modernization went in several directions. Perhaps the majority migrated to cities in Paraná and other southern states in search of jobs in industry and the service sector. Others remained in the agricultural sector as wage-earning day laborers (*boias frias*) and lived on the fringes of urban areas. Still others set off for the new agricultural frontier of Rondônia. The available data indicate that between 25 and 30 percent of the migrants to Rondônia over the past decade came from Paraná. Indeed, interest in migrating to Rondônia was so great that several bus companies set up ticket agencies in the main areas of outmigration. Although many of those who migrated from Paraná to Rondônia were undoubtedly lured by the prospect of fertile soils, cheap land, and government-financed infrastructure and services, the push exerted by the agricultural transformation of Paraná was also strong. One researcher, who interviewed migrants in a large settlement project in central Rondônia, found that more than 70 percent of those from Paraná had left the state either as a result of mechanization or because they could not support their family on a small piece of farmland, two closely related aspects of agricultural modernization (Calvente 1980).

or staked out claims on the fringes of the official projects, on Indian reservations, and in forest reserves. To defuse mounting social tensions over land rights, INCRA expanded existing settlement projects, recognized small squatters' claims, and sold large lots at public auctions. Despite these efforts the situation in Rondônia worsened in the late 1970s as continuing migration and budgetary cuts nearly paralyzed INCRA.

Map 4. Deforestation in Rondônia, 1983


AMAZONAS
ACRE
To Humaita
Pôrto Velho
Madeira R.
Jiparaná R.
BR-364
Abunã
Ariquemes
Alto Candeias
Guajará Mirim
MATO GROSSO
BOLIVIA
Vila Colorado
To Cuiaba
Amazon R.
BRAZIL
RONDÔNIA
Brasília
Atlantic Ocean
Atlantic Ocean
Pacific Ocean
Deforested areas
Selected roads
Natural reserves and Amerindian reservations
State boundaries
International boundaries
0 50 100 150 KILOMETERS
0 50 100 MILES

Rondônia's rapid population growth and uncontrolled settlement has had devastating effects on the rain forest (table 1). The speed at which this deforestation took place was, in some areas of the state, truly astonishing. The cleared area in the 80,000-hectare county (*município*) of Cacoal, for example, increased from 2,150 hectares in 1975 to 66,950 in 1978 (Fearnside 1982). Most of the deforestation was the result of clearing for agricultural purposes in the official settlement projects along the main highway (see map 4). Owing largely to the inadequacy of infrastructure, technical and financial assistance, agricultural research, and marketing facilities, however, most of the early settlers engaged in traditional and environmentally unsound farming practices (Mueller 1980).[7] These usually involved the clearing and burning of a patch of forest and the cultivation of annual crops for one to three years, depending on soil fertility. Pasture would then be established on the original patch, and the cycle would begin again with the clearing of another patch of forest.

By providing access to remote areas, Rondônia's network of feeder roads—which increased more than fivefold between 1975 and 1980 alone—greatly facilitated the deforestation process (IBGE 1986). Moreover, the poor condition of these roads and of BR-364 (especially during the rainy season) made it difficult to transport commodities to market and thus, along with other factors, discouraged the cultivation of tree crops such as cocoa, coffee, and rubber. From an environmental standpoint, tree crops are strongly preferred over annuals and pasture because of their superior ability to protect fragile soils from erosion. They also have important socioeconomic advantages: their cultivation is labor-intensive, and under reasonable market conditions they can provide a decent standard of living for a farm family. The principal disadvantages of tree crops are their susceptibility to disease (such as witches' broom fungus in cocoa and leaf blight in rubber), their costly fertilizer requirements when grown on the poor land typical of

---

[7] A particularly critical issue was the slow pace at which land titles were awarded. As of the end of 1979, only about 40 percent of the farmers in official settlement projects held a definitive title to their land. Farmers without titles were ineligible to receive investment credit.

Amazonia, and their generally weak prospects in international markets.

The growing socioeconomic problems in Rondônia led the government to reconstruct and pave BR-364 as part of a larger program of integrated regional development. The overall program, which covered the Northwest region of Brazil—a 410,000-square-kilometer area that includes all of Rondônia and part of western Mato Grosso—became officially known as the Northwest Brazil Integrated Development Program, or POLONOROESTE, in 1981 (map 3). Budgeted at US$1.5 billion, about a third of which was eventually provided by the World Bank (Mahar 1982), POLONOROESTE was expected to benefit the 30,000 or so families already settled in the Northwest as well as 15,000 families waiting to be settled in Rondônia.

A principal objective of POLONOROESTE was to reduce forest clearance on land with little long-term agricultural potential and to promote, instead, sustainable farming systems based on tree crops. The plan was to conduct land use surveys to identify areas with high potential and then to concentrate new access roads, social infrastructure, agricultural research and extension, input supplies, crop storage, marketing, and farm credit in those areas (FAO/CP 1987). Environmental protection services in the Northwest were also to be strengthened.

The available data indicate that the actions carried out under POLONOROESTE have neither slowed the pace of deforestation nor appreciably altered traditional patterns of land use. As mentioned previously, the deforested area of Rondônia, which comprised 3 percent of the state in 1980 (see table 1), increased to an estimated 24 percent by 1988. This implies that the average area deforested *annually* in this decade has been more or less equal to the *total* area already deforested by 1980! Moreover, the expected shift of farmland into tree crops has not materialized. Instead, as shown in table 5, there has been a rapid conversion of forest into pasture, one of the least desirable forms of land use in Amazonia from the environmental point of view. The experience of the SUDAM-approved projects strongly suggests that livestock activities provide little employment and are likely to be unsustainable in the long run.

Table 5. Agricultural Land Use in Rondônia, 1970–85
(square kilometers)

	Crops				
Year	*Annual*[a]	*Perennial*	*Pasture*	*Forest*[b]	*Total*[c]
1970	323.7	127.2	410.1	15,031.1	16,316.4
Percent	2.0	0.8	2.5	92.1	100.0
1975	1,503.9	457.6	1,645.2	26,681.4	30,820.5
Percent	4.9	1.5	5.3	86.6	100.0
1980	2,425.8	1,701.8	5,101.8	41,461.1	52,236.3
Percent	4.6	3.3	9.8	79.4	100.0
1985	3,153.3	2,238.0	15,611.5[d]	39,903.7[d]	60,906.6
Percent	5.2	3.7	25.6	65.5	100.0

a. Includes fallow land.
b. Includes natural pastures.
c. Area under farms at time of census; includes land unsuitable for agricultural use.
d. Estimated.
Source: IBGE (1987), Rondônia Secretariat of Planning, and author's estimates.

Several factors have contributed to the accelerated deforestation and inappropriate land use currently observed in Rondônia. An important proximate cause was the substantial jump in the migratory flow that followed the paving of BR-364 in 1984. About 160,000 migrants per year entered Rondônia in 1984–86, compared with an average of 65,000 per year in 1980–83. Although an appreciable number have moved on to newer frontier areas in the state of Acre to the west and the territory of Roraima to the north, the vast majority have stayed. As a result, Rondônia's population has grown at an average annual rate of almost 14 percent since 1980; in 1987 the population was estimated at 1.2 million. This rapid growth in population greatly increased the already heavy pressures on the forest. But population growth alone can explain neither the extremely rapid pace of deforestation nor farmers' preference for pasture formation over the cultivation of tree crops. The role of certain institutional and policy factors must therefore be considered.

Two institutional factors may be mentioned. First, the federal Institute of Forestry Development (IBDF) has not been able to enforce the so-called 50 percent rule, which prohibits landowners in

Amazonia from clearing more than half of their holdings.[8] Some settlers in Rondônia are reported to have cleared as much as 90 percent of their lots. In addition to its being unenforceable, some scientists argue that the rule may intensify the damage to the environment it is designed to prevent (Goodland and Irwin 1975, p. 30). Animals and plants need a certain amount of space to survive. For insects the minimum area needed may be measured in square meters; for large mammals, such as the jaguar, 500,000 or more hectares may be necessary to support a genetically viable population. The 50-hectare reserve in a typical colonist's lot, therefore, will not sustain anywhere near the level of biological diversity found in undisturbed rain forest. In addition, the on-farm reserves may harbor plant and insect pests which attack the surrounding agricultural areas.

Second, the intensification of smallholder agriculture envisaged under POLONOROESTE was predicated on the assumption that subsidized credit would be made available to finance purchases of modern inputs. The use of fertilizers and other inputs was particularly important for those farmers who were settled by INCRA on poor soils. Early in the implementation of the program, however, austerity measures forced a reduction in both the subsidy element and the supply of credit (see table 4). As a result, most farmers in the Northwest were unable to obtain credit. But even when credit was available, many farmers were reluctant to use it because they felt that the subsidy element was not high enough to offset the risks associated with the cultivation of tree crops (Wilson 1985). The problems caused by the lack of credit were compounded by an extension service which continued to promote farm models with large input requirements (FAO/CP 1987).

In addition to these institutional factors, certain land and tax policies have encouraged (or at least have not discouraged) unnecessary deforestation and inappropriate land use. Indeed, unless these policies are substantially modified, it is doubtful that land use patterns in the Northwest can be improved. The policy environment in Rondônia differs in many ways from that in eastern Amazonia. Fiscal incentives for livestock development, for example, have not been an important factor: fewer than 20 of the 631 SUDAM-approved projects are in Rondônia. This is mainly the result of a 1971 law which provides that all land in Amazonia located within 100 kilometers of a federal highway (such as BR-364), or within 150 kilometers of an international boundary, falls under federal control. In effect, this law placed more than 90 percent of the area of Rondônia under the jurisdiction of INCRA. The policies of INCRA, therefore, have had a much greater impact on land use than those of other government agencies.

---

[8] The penalty for exceeding legal limitations on deforestation is a one-time fine equivalent to approximately US$1,000, a prohibitive sum for small farmers. Large landowners, however, may be able to sell timber cut from the 50 percent legal reserve for more than the value of the fine.

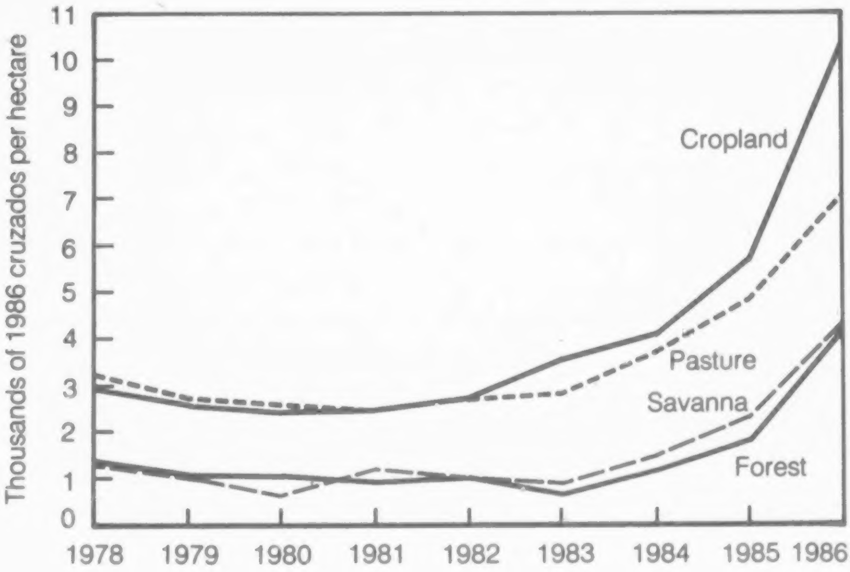
Some of INCRA's policies have encouraged inappropriate land use. Foremost among these is its acceptance of deforestation as evidence of land improvement: a migrant in an official settlement project or an invaded area can obtain rights of possession simply by clearing the forest.[9] Both good and poor lands are deforested indiscriminately as a result. The geographical extent of these rights are determined by multiplying the cleared area by three, up to a maximum of 270 hectares. Once obtained, rights of possession can be sold either formally or informally, depending on whether the migrant has occupied the land long enough to qualify for a definitive title. Although some migrants with a serious interest in developing sustainable agriculture have benefited from this policy, many others have used it simply to acquire land for speculative purposes.

The potential gains from speculation would appear to be very high in Rondônia. As shown in figure 2, real prices of land have soared in recent years, largely in response to continued migration and the improvements in roads and other infrastructure financed through POLONOROESTE. The prospect of realizing large capital gains has induced many migrants to sell their lots. In the older settlement projects an estimated 80 percent of the lots have al-

---

[9] Settlers who wish to engage in extractive activities that do not disturb the forest—for example, rubber tapping or the gathering of Brazil nuts—are particularly disadvantaged by this policy.

Figure 2. Average Land Prices in Rondônia, 1978–86



ready been sold; in newer settlement areas turnover rates range from 40 to 55 percent.

Calculations made by the FAO/World Bank Cooperative Program (FAO/CP), which recently reviewed the interim results of POLONOROESTE, show that it is possible for speculators to net the equivalent of US$9,000 if they clear fourteen hectares of forest, plant pasture and subsistence crops for two years, and then sell the rights of possession acquired by doing so. This constitutes a large sum of money in Rondônia, where the average daily farm wage is equivalent to less than US$6.00. Additional calculations by the FAO/CP show that even bona fide farmers who plant tree crops stand to make handsome profits by selling their lots after a few years (FAO/CP 1987, annex 5, table 1). In theory, such gains on land sales would be taxed at a flat rate of 25 percent. In practice, however, few of these capital gains are taxed, particularly in frontier areas, because many land transactions are handled informally and sales prices are underreported. Binswanger (1987) argues that, by exempting virtually all agricultural income from taxation, provisions of the income tax code tend to increase the demand for land among individuals with high incomes. These provisions thus contribute to a more rapid conversion of forest to agricultural uses as well as to land price appreciation and concentration of land ownership.

The rural land tax (ITR), which is administered by INCRA, also encourages deforestation, at least in theory. The ITR was created in 1964 with the laudable objective of encouraging more productive use of land. The tax is currently assessed at a maximum rate of 3.5 percent of the market value of the land; the required 50 percent forest reserve is exempted from taxation. Reductions of up to 90 percent in the basic rate are given according to the degree of utilization of land (that is, the proportion cleared) and certain "efficiency" indicators—for example, crop yields, cattle stocking rates, rubber extraction per hectare—established by INCRA. In practice, the ITR probably has little influence on patterns of land use, mainly because the landowners themselves declare the value of their land as well as the efficiency of its use. According to INCRA, only about half of all registered landowners in Rondônia paid any ITR in 1986; the average payment of those who did was equivalent to only US$5.00!

The rapid pace of pasture formation (a process known as *pecuarização*) recently observed in Rondônia appears to be largely the result of the institutional and policy factors discussed above combined with one more factor: the poor quality of the land in the settlement areas. Without the resources to pay for the fertilizers and other modern inputs needed to cultivate tree crops on poor soil as well as for wage labor to help with the planting and harvesting, settlers often find that pasture formation is their only option (short of selling their lots). Interviews with small farmers in Rondônia indicate that they consider cattle to be a form of social security which in times of need can be sold to repay bank credit, finance medical care and schooling, and so forth (Milliken 1984). Speculators also prefer to keep their land in pasture because the maintenance costs are lower than for crops. Such persons can even avoid the initial financial outlays for clearing the forest and planting the pasture by having landless migrants perform these tasks in exchange for permission to cultivate the newly cleared land for one or two seasons. Both the state and federal authorities in Rondônia should give priority to the collection and analysis of field data on the factors driving unproductive *pecuarização* and related land speculation as well as to the implementation of measures to halt these processes.

The Era of Big Projects

In the mid-1970s the government essentially abandoned the road-building and directed settlement strategy embodied in PIN and focused instead on the development of large-scale export-oriented projects in the livestock, forestry, and mining sectors in fifteen "growth poles" scattered throughout Amazonia. The Program of Agricultural, Livestock, and Mineral Poles in Amazonia, or POLAMAZONIA (it was established in 1974 and abolished in 1987) was essentially a program of infrastructure development which, combined with existing fiscal and credit incentives, sought to create a more favorable investment climate in Amazonia for private enterprise. The small-scale farmer, although relegated to a lower priority in regional plans, was not totally neglected. Recent official settlement programs, however, have been almost exclusively concerned with accommodating through POLONOROESTE the surge of spontaneous migration to Rondônia.

One factor explaining the abrupt shift away from directed small-scale settlement was general disillusionment with the Transamazon experience and the realization in government circles that Amazonia could not provide a quick fix to the demographic pressures and socioeconomic problems of the Northeast. Another important factor was the oil crisis of 1973, which hit Brazil, a major importer of this commodity, particularly hard. This external shock put into serious question the strategy of integrating Amazonia with the rest of Brazil on the basis of the automobile and truck. It also greatly increased the country's requirements for foreign exchange to pay for oil imports and to service the rapidly mounting external debt. The government felt that exports of Amazonian minerals, timber, and agricultural products could make an important contribution to Brazil's annual foreign exchange earnings.

Current regional policy has focused on the development of the mining and mining-related sectors of eastern Amazonia. Official interest in the mining potential of this subregion dates from 1967, when a U.S. Steel geologist accidentally discovered in the remote

Serra dos Carajás (located 550 kilometers south of Belém in Pará) a virtual mountain of high-grade (66 percent pure) iron ore, with estimated reserves of 18 billion tons. Subsequent prospecting in the area uncovered extensive reserves of copper, manganese, cassiterite, nickel, bauxite, and gold. To exploit the area's natural resources in a rational manner, the government established the Greater Carajás Program (PGC) in 1980. The PGC is administered by an interministerial council headed by the minister of planning. The program area comprises 895,000 square kilometers (more than 10 percent of Brazil's total land area, see map 3) and contains four of POLAMAZONIA's planned growth poles. Within this area, firms approved by the interministerial council enjoy generous fiscal incentives, government guarantees of foreign and domestic credit operations, and subsidized energy from the nearby Tucuruí hydroelectric facility.[10]

The first major project in the Carajás subregion set out to exploit the region's huge reserves of iron ore. Approved by the Economic Development Council in 1978 and carried out under the responsibility of Companhia Vale do Rio Doce (CVRD), the Carajás Iron Ore Project began implementation in 1983 and is now fully operational. Besides development of the mine site, the project also involved the construction of a 890-kilometer railroad from the mine head to São Luís in Maranhão, port facilities capable of handling the mine's annual output of 35 million tons, and urban infrastructure. CVRD's concession area totals 4,290 square kilometers, plus a narrow strip on either side of the railroad. The cost of the project, including contingencies, was around US$5 billion. Financing was provided by CVRD (40 percent) and national and foreign creditors, including the World Bank, which provided US$300 million.

---

[10] The Tucuruí facility, which began operating in 1984, currently generates about 2,000 megawatts of power. Its generating capacity could reach 7,960 megawatts at full development. The lake formed by the facility extends 200 kilometers up the Tocantins River and covers an area of 2,435 square kilometers. The original intention was to harvest the timber on the land to be inundated by Tucuruí, but the firm that was awarded the contract to do so was inexperienced and eventually went bankrupt. As a result, millions of cubic meters of commercially valuable timber were lost.

Unlike most other projects in Amazonia, the Carajás Iron Ore Project was developed with close attention to its possible effects on the environment. CVRD had obviously learned from its own experience in southern Brazil, as well as from the experience of others in Amazonia, where mining has seldom been undertaken with due regard for the natural environment. Even before the Carajás project had been officially approved, CVRD commissioned a series of environmental baseline studies of the proposed project area. The studies covered climatology, ecology, botany, and related disciplines and provided a framework for the development of company policies regarding forest clearing, topsoil stockpiling, erosion control, vegetation regeneration, protection of fauna, and other environmental matters. Spelled out in a manual, these policies eventually became the basis of the project's environmental components (Freitas 1982).

Between 1981 and 1985, CVRD spent around US$54 million on environmental activities related to the Carajás project (Kohlhepp 1987). These activities included land reclamation, the creation of protected natural reserves, and the promotion of environmental awareness and training. Physical access to the project area was tightly controlled to prevent unplanned human occupation. To oversee the implementation of the project's environmental components, CVRD created an independent group of nine senior scientists who were to visit the project site periodically over fifteen years. In addition, internal environmental commissions made up of CVRD employees and contractors and coordinated by an ecologist were placed on site permanently to make sure that government and company environmental guidelines were adhered to (Freitas 1982).

In contrast to the orderly and environmentally responsible development of the Carajás iron ore reserves, the situation in the PGC area outside of the CVRD concession has been chaotic. Migration to the Greater Carajás area has been intense in recent years. For example, the *município* of Marabá, which includes the Serra dos Carajás, more than doubled in population (from 60,000 to 134,000) between 1980 and 1985. Some of the migrants have been drawn by the opportunities for employment—for example, in connection with the construction of the Tucuruí dam and various civil works related to the iron ore project; others by the prospect of striking it rich in newly discovered goldfields. Because this subregion of Amazonia had already been subjected to settlement and large-scale cattle ranching once before, following the completion of the Belém-Brasília highway, the recent spurt in population growth has exacerbated the problems that have characterized much of the PGC area for many years—accelerated deforestation, environmental degradation, and violent conflicts over land rights (Branford and Glock 1985).

Although the program has been in existence for the better part of a decade, the PGC has yet to come up with a realistic, environmentally sound development plan for the overall subregion. In 1980, at the request of CVRD, Japanese consultants prepared a plan that called on the private sector to develop export-oriented projects in the mining, metallurgy, agriculture, livestock, and forestry sectors. The plan would have required investments of US$62 billion, however, and nowhere near this amount has materialized. In 1983, the Ministry of Agriculture published a US$1.2 billion plan to divide the PGC area into seven agricultural poles. Undertakings within these poles would include 238,000 hectares of soybeans, 12,600 hectares of sugarcane, and 417,000 hectares of cattle pasture. In addition, 3.6 million hectares along the Carajás–São Luís railway would be set aside for eucalyptus plantations which would provide charcoal for metallurgical use (Hall 1987 and Fearnside 1986a).

The PGC agricultural development plan has been severely criticized for being inequitable (only 17 percent of the land would be allocated to small producers) and for promoting forms of land use (such as cattle ranching, annual cropping, and homogeneous tree plantations) which are not likely to be sustainable (Hall 1987 and Fearnside 1986a). Like the grandiose plan prepared earlier by Japanese consultants, the agricultural plan will probably never be implemented in its entirety. But plans to develop a metallurgical sector along the railway corridor on the basis of locally produced iron ore and charcoal are moving ahead. Fifteen pig iron and manganese iron projects had been approved for fiscal incentives by the interministerial council of the PGC by late 1987; at least two are expected to begin operations in 1988.[11] Another fifteen projects are currently under consideration.

The long-term viability—economic, financial, and environmental—of the metallurgy and charcoal projects has not yet been established. On the contrary, the available information casts doubt on the whole enterprise. The implementation of proposed projects would, at a minimum, add appreciably to pressures on the forest. Preliminary estimates suggest that the pig iron plants would, at full operation, require 1.2 million tons of charcoal per year. To satisfy this demand, between 90,000 and 200,000 hectares of forest would have to be cut each year, depending on tree stands, density of species used, and other factors. Because wood from the proposed eucalyptus plantations would not be available until the seventh year after planting, the total deforestation attributable to the pig iron plants would reach between 540,000 and 1.2 million hectares. The environmental implications of such large-scale deforestation are clearly negative.

No analysis of the true economic costs of producing pig iron using charcoal has been made. It is estimated, however, that (based on gross revenues from pig iron exports of US$100–110 per ton) any fuel in the Carajás area which costs less than US$70 per ton of charcoal equivalent would render the plants profitable. Charcoal produced from the virgin forest, which currently sells for US$27 per ton in the region, clearly falls into this category. A recent study commissioned by SUDAM (1986) reached a similar conclusion. But market prices for charcoal reflect only the cutting and transportation costs for the wood used in its manufacture. Were the full environmental costs of deforestation to be included in the price of charcoal, it is by no means clear that the plants would remain viable. A key question, therefore, is whether charcoal can be produced at competitive prices from exotic trees.

---

[11] The PGC offers several types of fiscal incentives to approved firms. The most generous of these allows firms for a period of ten years to take a tax credit equal to 50 percent (reduced from 100 percent in 1985) of their corporate income tax liabilities on income earned within the PGC area if this money is reinvested in projects approved by the interministerial council. "Fresh money" must account for at least 25 percent of any new investments using tax credit funds. To date, the beneficiaries of tax credits have all been construction or engineering firms with profits from civil works projects in the PGC area. Other fiscal incentives offered by the PGC include exemptions from import duties and the federal excise tax (IPI).

Unfortunately, the cost of producing charcoal from plantation-grown eucalyptus—on the scale envisioned and under the agronomic and climatic conditions prevailing in the Carajás area—is not known with certainty. The dismal historical experience with homogeneous tree plantations in Amazonia suggests that the cost will be high, however. In a recent article Fearnside (1987) estimates that to supply the proposed pig iron plants with charcoal derived entirely from plantation-grown eucalyptus would involve the planting of 2.6 million hectares of trees. This is thirty-five times the size of the largest eucalyptus plantation in Amazonia, the 76,000 hectares planted on the Jari holdings in northeastern Pará. The Jari project's tree plantations, despite massive injections of capital and intensive experimentation and research, proved to be far more expensive and less productive than originally thought and have yet to turn a profit (Fearnside 1987 and Kinkead 1981).

All in all, the experience accumulated during the era of big projects suggests that the impact of government policies on the Amazon rain forest has been generally negative. The Carajás Iron Ore Project, however, has shown that it is possible to exploit the region's resources in a manner which minimizes environmental damage. But it must be emphasized that the success of the iron ore project is largely attributable to the intrinsic nature of mining—usually a small area is involved and production is not dependent on environmental factors such as soils and climate—and to CVRD's environmentally sensitive approach and its ability to control events in its concession area. These circumstances will not be easy to replicate elsewhere in Amazonia. This point is vividly illustrated by recent and projected developments in the Greater Carajás area outside of the CVRD concession, in the areas of large-scale livestock development scattered throughout Amazonia, and in Rondônia.

Conclusions and Recommendations

Over the past twenty-five years the Brazilian government's policies to develop the Amazon region have rarely been designed and carried out with due regard for their environmental consequences.

The felling of the rain forest, which began on a large scale during the 1970s, continues at an accelerated pace in many parts of the region. The forests of Rondônia and parts of eastern Amazonia, in particular, are being cleared at explosive rates. Much of this deforestation has benefited neither the regional population nor Brazilian society as a whole, except perhaps in the very short term. Despite decades of intense development, Amazonia still accounts for only an insignificant 3 percent of the national income.[12]

Many of today's problems can be traced to the decision in the mid-1960s to provide overland access to Amazonia—a decision made before enough was known about the region's natural resource base and how to develop it in a sustainable manner. This initial error was compounded by subsequent decisions to provide generous incentives to investors willing to undertake environmentally questionable livestock projects and, more recently, smelting projects in the Greater Carajás area. Official settlement projects have also contributed to deforestation, although it would be wrong to place all of the blame on the settlers. Pushed by poverty and skewed land distributions in their regions of origin, the settlers have merely responded to incentives created by the government in the form of access roads, titles to public lands, various public services, and, in the case of the Transamazon scheme, subsistence allowances.

There is no doubt that rapid deforestation will continue if present policies remain unaltered. In areas where overland access already exists, much damage has already been done. In such areas the government should do what it can to promote the recuperation of degraded and abandoned lands and thus help to restore the forest's biological diversity. In areas where the land is being used for small-scale agriculture, the best course of action would be to increase public support—both technical and financial—for those activities which can provide a decent living for a farm family and also minimize additional environmental damage. Such activities might include the cultivation of tree crops, the gathering of forest products, subsistence livestock (dairy cows, pigs, and chickens, for example), or some mixed production system. Because the costs of production are relatively high in remote frontier areas and the market prospects for many of Amazonia's key exports are uncertain, this approach might require some degree of subsidization by the government. Such subsidies could be justified on both environmental and equity grounds, however.

---

[12] This figure was calculated using standard national accounting procedures which charge the depreciation of man-made assets (for example, buildings and equipment) against current income, but not the depletion of natural resources (for example, wildlife, minerals, and trees). Were this anomaly corrected, the real level of income generated in Amazonia would undoubtedly be much lower.

A new policy should be developed for rain forest areas for which overland access does not yet exist. This policy would differ considerably from past policies which have focused on opening up Amazonia indiscriminately for small- and large-scale agricultural and livestock development: in effect, it would introduce an alternative development model that emphasizes the region's comparative advantage in forest-based economic activities. Under this approach the government would not construct any new roads or provide infrastructure or services (particularly land titles) until detailed land use surveys were carried out. Once the appropriate surveys were completed and the productive potential of the land known, physical access would be permitted only under special circumstances. (To reduce pressures for additional road construction, it would be useful to improve water transport facilities in these areas.) Lands found to have limited agricultural potential—virtually all of the *terra firme* of Amazonia—would be held in perpetuity as forest reserves closed to all development or as sites for environmentally benign activities such as rubber tapping and Brazil nut gathering, tourism, or sustained-yield logging.

Recent events in Brazil suggest that a change in regional development policy along the lines suggested above may be in the offing. The government of Rondônia, for example, proposed in mid-1987 that the entire state be subject to agroecological zoning. The federal government is considering the possibility of extending this concept to all of Amazonia. These are definitely steps in the right direction. It should be kept in mind, however, that the government first proposed agroecological zoning for Amazonia in the late 1970s. A special commission composed of academics and government representatives was set up to draft suitable legislation. The original draft legislation included a commitment to preserve 150 million hectares of the region, 100 million hectares of which were to be rain forest. The preservationist tone of the document was softened considerably in subsequent revisions, reportedly as a result of intense lobbying by timber and cattle companies and private colonization firms. In the event, no version of the legislation was ever approved by Congress.

The success or failure of the new attempts to apply agroecological zoning in Amazonia will depend largely on the technical quality of the proposals, the strength and depth of political support for the concept, and the existence of an overall policy framework consistent with rational land use. It is too early to pass judgment on the first two factors, but it is clear from the analysis in this pamphlet that a suitable policy framework is still not in place. Some recommendations on how the current policy framework could be improved follow.

First, the government might consider eliminating fiscal incentives for livestock projects in Amazonia. Disbursements to projects already under implementation could continue, but only in cases where SUDAM has confirmed by field visits that such projects are not located in rain forest areas. More than two decades of experience have shown that livestock projects have been responsible for much environmental damage and yield little in the way of production or employment. Livestock projects may also be criticized on equity grounds because most of the benefits from the fiscal subsidy have accrued to a small group of wealthy investors who have used these resources to appropriate large tracts of land on the agricultural frontier. Clearly, SUDAM-approved livestock projects have not succeeded in generating the social benefits necessary to justify the continuation of government subsidies.

The possibility of abolishing all regional fiscal incentives has been considered as part of Brazil's overall tax reform program. But owing to strong lobbying on the part of regional and extraregional special interest groups, this is unlikely to occur in the near future. The most powerful lobby group supporting the fiscal incentives for cattle ranching has traditionally been the Association of Amazonian Entrepreneurs (AEA), which is based in São Paulo (Pompermayer 1984). Local political interests have also shown little enthusiasm for eliminating what is viewed as an important source of investment capital for the region.

Second, the government might consider declaring a moratorium on disbursements of fiscal incentive funds for any projects in the Greater Carajás area—such as the proposed pig iron plants—which would use charcoal derived from the rain forest as their principal source of energy. Projects of this type threaten to cause considerable deforestation and in return would yield products of relatively little value. Although these projects would in theory be obliged to replace the forest with tree plantations, previous attempts to establish large-scale tree plantations in Amazonia have never succeeded. Before a final decision is made on these projects, further research should be carried out on their true economic costs (including the environmental costs) and on the possibility of using alternative energy sources such as electricity from Tucuruí or natural gas.

Third, INCRA might consider modifying its policy of recognizing deforestation as a form of land improvement and, as such, as grounds for granting rights of possession. This policy has encouraged felling of forest in areas with little or no agricultural potential. It has also fueled land speculation. In the future INCRA should not grant rights of possession or definitive titles to any lots on poor soils. In areas with poor soils but with potential for extractive activities, the granting of long-term concessions should be considered. INCRA has recently proposed a modification of its land use policies along these lines. It plans to provide twenty- to thirty-year concessions to individuals (mostly rubber tappers already in the region) or producer associations that undertake environmentally sound extractive activities in designated areas. This approach, which fits well with current proposals calling for agroecological zoning, should be encouraged.

Fourth, IBDF might consider abolishing the 50 percent rule. It has been shown to be unenforceable in a frontier region such as Amazonia and provides little, if any, protection to the environment. In place of the rule, legislation should be passed which expressly permits the formation of contiguous "block" reserves equal to 50 percent of the total area under agriculture in a given region rather than 50 percent of each farmer's lot. Such reserves would help to maintain biological diversity, benefit agriculture, and increase the number of migrants who could be settled on better soils in already occupied areas. As part of an experiment, block reserves have been established in some of the newer settlement areas of Rondônia. Although some problems have been reported—for example, illegal invasions of the reserves and disputes among settlers over their individual rights to use them—the experiment should be closely monitored and evaluated for its replicability in other parts of Amazonia.

Fifth, the government should increase its efforts to improve the administration of taxes which, if duly collected, could have beneficial effects on land use. A more effective administration of the 25 percent tax on capital gains from land appreciation, for example, could help dampen speculative pressures. The progressive rural land tax has the potential to improve land use patterns by penalizing those who engage in environmentally unsound activities. The structure of the tax would have to be modified for Amazonia, however, to allow land left in virgin forest to be considered productive and thus to qualify for the lowest tax rate. Administration of this tax would also have to be vastly improved.

The above list of recommendations is not exhaustive. It does not, for example, include measures to improve employment opportunities in northeastern and southern Brazil and hence reduce pressures on the rural poor to migrate to the Amazonian frontier. Undoubtedly, there is much that could be accomplished in this regard. Nevertheless, if the policy reforms suggested were to be combined with a well-thought-out and well-executed zoning plan for Amazonia, further economic losses and much unnecessary deforestation would be avoided in the future.

References

BASA (Banco da Amazonia). 1981. *FINAM: Legislação Básica dos Incentivos Fiscais para a Região Amazônica.* Belém.

Binswanger, Hans. 1987. "Fiscal and Legal Incentives with Environmental Effects on the Brazilian Amazon." Agriculture and Rural Development Department, World Bank, Washington, D.C. Processed.

Branford, Sue, and Oriel Glock. 1985. *The Last Frontier: Fighting Over Land in the Amazon*. London: Zed Books.

Brazil, Comissão Parlamentar de Inquérito sobre a Devastação da Amazônia e suas Implicações. 1978. *Depoimento do Dr. Hugo de Almeida, Ex-Superintendente da SUDAM e Atual Presidente do IAA, Prestado no Dia 19 de Junho de 1978*. Brasília.

Browder, John O. 1988. "Public Policy and Deforestation in the Brazilian Amazon." In Robert Repetto and Malcolm Gillis, eds. *Public Policies and the Misuse of Forest Resources*. London: Cambridge University Press.

Bunker, Stephen G. 1981. "The Impact of Deforestation on Peasant Communities in the Medio Amazonas of Brazil." *Studies in Third World Societies* 13: 45–60.

Calvente, Átila T. 1980. "Formações Não Capitalistas no Movimento de Ocupação da Amazônia: Colonização Agrícola em Rondônia—1970/1980." Master's thesis, University of Brasília.

Carnasciali, Carlos H., and others. 1987. "Consequências Sociais das Transformações Tecnológicas na Agricultura do Paraná." In George Martine and R. C. Garcia, eds. *Os Impactos Sociais da Modernizaçãco Agrícola*. São Paulo: Editora Hucitec.

Collins, Jane L. 1986. "Smallholder Settlement of Tropical America: The Social Causes of Ecological Destruction." *Human Organization* 45, no. 1: 1–9.

Denevan, William H. 1973. "Development and the Imminent Demise of the Amazon Rain Forest." *Professional Geographer* 25: 130–35.

FAO/CP (Food and Agriculture Organization/World Bank Cooperative Program). 1987. "Brazil: Northwest I, II, and III Technical Review Final Report." Rome. Processed.

Fearnside, Philip M. 1982. "Deforestation in the Brazilian Amazon: How Fast Is It Occurring?" *Interciencia* 7, no. 2: 82–88.

Fearnside, Philip M. 1983. "Development Alternatives in the Brazilian Amazon: An Ecological Evaluation." *Interciencia* 8, no. 2: 65–78.

Fearnside, Philip M. 1986a. "Agricultural Plans for Brazil's Grande Carajás Program: Lost Opportunity for Sustainable Local Development?" *World Development* 14, no. 3: 385–409.

Fearnside, Philip M. 1986b. *Human Carrying Capacity of the Brazilian Rainforest*. New York: Columbia University Press.

Fearnside, Philip M. 1986c. "Spatial Concentration of Deforestation in the Brazilian Amazon." *Ambio* 15, no. 2: 74–81.

Fearnside, Philip M. 1987. "Jari aos Dezoito Anos: Lições para os Planos Silviculturais em Carajás." In Gerd Kohlhepp and Achim Schrader, eds. *Homem e Natureza na Amazônia*. Tübinger Geographische Studien no. 95. Tübingen: Tübingen University.

FGV/CEA (Fundação Getúlio Vargas, Centro de Estudos Agrícolas). 1985. *Agropecuária: Preços Médios de Arrendamentos, Vendas de Terras, Salários, Empreitadas, e Transportes*. Rio de Janeiro.

Freitas, Maria de Lourdes Davies de. 1982. "Brazil's Carajás Iron Ore Project: Environmental Aspects." Companhia Vale do Rio Doce, Rio de Janeiro. Processed.

Garcia Gasques, José, and Clando Yokomizo. 1986. "Resultados de 20 Anos de Incentivos Fiscais na Agropecuária da Amazônia." *XIV Encontro Nacional de Economia*, ANPEC 2: 47–84.

Goodland, Robert J. A. 1980. "Environmental Ranking of Amazonian Development Projects in Brazil." *Environmental Conservation* 7, no. 1: 9–26.

Goodland, Robert J. A., and H. S. Irwin. 1975. *Amazon Jungle: Green Hell to Red Desert?* Amsterdam: Elsevier Scientific Publishing Co.

Goulding, Michael. 1983. "Amazonian Fisheries." In E. F. Moran, ed. *The Dilemma of Amazonian Development*. Boulder, Colo.: Westview Press.

Guppy, Nicholas. 1984. "Tropical Deforestation: A Global View." *Foreign Affairs* 62, no. 4: 928–65.

Hall, Anthony. 1987. "Agrarian Crisis in Brazilian Amazonia: The Grande Carajás Programme." *Journal of Development Studies* 23, no. 4: 522–52.

Hecht, Susanna B. 1985. "Environment, Development and Politics: Capital Accumulation and the Livestock Sector in Eastern Amazonia." *World Development* 13, no. 6: 663–84.

Hecht, Susanna B., R. B. Norgaard, and G. Possio. n.d. "The Economics of Cattle Ranching in Eastern Amazonia." Graduate School of Architecture and Urban Planning, University of California, Los Angeles. Processed.

IBGE (Instituto Brasileiro de Geografia e Estatística). 1983. *Censo Agropecuário—1980.* Rio de Janeiro.

IBGE. 1987. *Sinópse Preliminar do Censo Agropecuário—1985.* Rio de Janeiro.

IBGE. Various years. *Anuário Estatístico do Brasil.* Rio de Janeiro.

Katzman, Martin T. 1977. *Cities and Frontiers in Brazil.* Cambridge, Mass.: Harvard University Press.

Kinkead, Gwen. 1981. "Trouble in D. K. Ludwig's Jungle." *Fortune* (August 20): 102–17.

Knight, Peter, and others. 1984. *Brazil: Financial Systems Review.* Washington, D.C.: World Bank.

Kohlhepp, Gerd. 1987. "Problemas do Planejamento Regional e do Desenvolvimento Regional na Área do Programa Grande Carajás no Leste da Amazônia." In Gerd Kohlhepp and Achim Schrader, eds. *Homen e Natureza na Amazônia.* Tübinger Geographische Studien no. 95. Tübingen: Tübingen University.

Ledec, George. 1985. "The Environmental Implications of Agricultural Credit Programs: Preliminary Findings for Brazil." Department of Political Science, University of California, Berkeley. Processed.

Mahar, Dennis J. 1976. "Fiscal Incentives for Regional Development: A Case Study of the Western Amazon Basin." *Journal of Interamerican Studies and World Affairs* 18, no. 3: 357–78.

Mahar, Dennis J. 1978. "Políticas do Desenvolvimento para a Amazônia: Passado e Presente." In Werner Baer, P. P. Geiger, and P. R. Haddad, eds. *Dimensões do Desenvolvimento Brasileiro.* Rio de Janeiro: Editora Campus.

Mahar, Dennis J. 1979. *Frontier Development Policy in Brazil: A Study of Amazonia.* New York: Praeger Publishers.

Mahar, Dennis J. 1982. "Instituições Internacionais de Empréstimo Público e o Desenvolvimento da Amazônia Brasileira: A Experiência do Banco Mundial." *Revista de Administraçãco Pública* 16, no. 4: 23–38.

Mahar, Dennis J., and others. 1981. *Brazil: Integrated Development of the Northwest Frontier.* Washington, D.C.: World Bank.

Margolis, Maxine L. 1973. *The Moving Frontier: Social and Economic Change in a Southern Brazilian Community.* Gainesville: University of Florida Press.

Martine, George. 1980. "Recent Colonization Experiences in Brazil: Expectations versus Reality." In Françoise Barbira-Scazzocchio, ed. *Land, People and Planning in Contemporary Amazonia.* Cambridge: Cambridge University Press.

Martine, George. 1988. "Changes in Agricultural Production and Rural Migration." Institute of Economic and Social Planning, Brasília. Processed.

Millikan, Brent H. 1984. "Diagnóstico de Dez Núcleos Urbanos de Apoio Rural." Del Mar, Calif. Processed.

Moran, Emilio F. 1981. *Developing the Amazon.* Bloomington: Indiana University Press.

Mueller, Charles C. 1980. "Recent Frontier Expansion in Brazil: The Case of Rondônia." In Françoise Barbira-Scazzocchio, ed. *Land, People and Planning in Contemporary Amazonia.* Cambridge: Cambridge University Press.

Myers, Norman. 1984. *The Primary Source: Tropical Forests and Our Future.* New York: W. W. Norton.

Myers, Norman. 1986. "Tropical Forests: Patterns of Depletion." In Ghillean T. Prance, ed. *Tropical Rain Forests and the World Atmosphere*. Boulder, Colo.: Westview Press.

Oliveira, Francisco de. 1978. "O Café e o Norte do Paraná." In Instituto Brasileiro do Café. *O Café no Brasil*. Rio de Janeiro.

Paula, Ruben D. de Garcia. 1971. "A Rodovia Belém-Brasília e os Fazedores de Desertos." *A Amazônia Brasileira em Foco* 6: 78–95.

Pompermayer, Malori J. 1984. "Strategies of Private Capital in the Brazilian Amazon." In Marianne Schmink and C. H. Wood, eds. *Frontier Expansion in Amazonia*. Gainesville: University of Florida Press.

Prance, Ghillean T. 1986. "Introduction to Tropical Rain Forests." In Ghillean T. Prance, ed. *Tropical Rain Forests and the World Atmosphere*. Boulder, Colo.: Westview Press.

Resende, Eliseu. 1973. *As Rodovias e o Desenvolvimento do Brasil*. Rio de Janeiro: Ministério dos Transportes.

Resor, Randolph. 1977. "Rubber in Brazil: Dominance and Collapse, 1876–1945." *Business History Review* 51, no. 3: 341–66.

Santos, Roberto. 1980. *História Econômica da Amazônia: 1800–1920*. São Paulo: T. A. Queiroz.

Sawyer, Donald. 1984. "Frontier Expansion and Retraction in Brazil." In Marianne Schmink and C. H. Wood, eds. *Frontier Expansion in Amazonia*. Gainesville: University of Florida Press.

Smith, Nigel J. H. 1981. "Colonization Lessons from a Tropical Forest." *Science* 214, no. 4,522: 755–61.

Smith, Nigel J. H. 1982. *Rainforest Corridors: The Transamazon Colonization Scheme*. Berkeley: University of California Press.

SUDAM (Superintendência do Desenvolvimento da Amazônia). 1986. *Problemática do Carvão Vegetal na Área do Programa Grande Carajás*. Belém.

U.S. Department of Energy. 1986. *A Comparison of Tropical Forest Surveys*. Washington, D.C.

Wilson, John F. 1985. *Ariquemes: Settlement and Class in a Brazilian Frontier Town*. Ph.D. diss., University of Florida, Gainesville.

Wolf, Edward C. 1988. "Avoiding a Mass Extinction of Species." In L. R. Brown, ed. *State of the World 1988*. New York: W. W. Norton.

Woodwell, George M., R. A. Houghton, and T. A. Stone. 1986. "Deforestation in the Brazilian Amazon Basin Measured by Satellite Imagery." In Ghillean T. Prance, ed. *Tropical Rain Forests and the World Atmosphere*. Boulder, Colo.: Westview Press.

World Resources Institute. 1985. *Tropical Forests: A Call for Action*. Part I: *The Plan*. Washington, D.C.

The Osborn Center for Economic Development

A Program of World Wildlife Fund
and The Conservation Foundation

1250 Twenty-Fourth Street, N.W.
Washington, D.C. 20037 U.S.A.

Telephone: (202) 293-4800
Facsimile: (202) 293-9211
Telex: 64505 PANDA

The Osborn Center for Economic Development is a joint program of World Wildlife Fund and The Conservation Foundation. Its purpose is to foster economically and environmentally sustainable development by promoting wise management and efficient use of natural resources as a central element in the economic development process.

ISBN 0-8213-1174-3

PLAN FOR AMAZON BACKED IN BRAZIL

Experiment Seeks to Protect the Jungle While Allowing Profitable Ventures

By MARLISE SIMONS

Special to The New York Times

RIO DE JANEIRO, July 2 — A patch of undisturbed jungle in the Amazon has been chosen for an experiment that could bring about a revolution in the way man deals with the largest remaining tropical rain forest on earth.

The experiment aims to develop ways in which the forest people can cut precious hardwood trees, collect more rubber, nuts, spices and useful plants, and protect the forest at the same time they make a profit.

If successful, foresters and economists believe, the experiment can serve as a model to manage similar vegetation throughout the Western Amazon, which reaches from Brazil into neighboring Bolivia, Peru, Venezuela and Colombia.

Such forest management would require a regional policy to deal with the settlers, loggers, miners and cattlemen who are now carving away the jungle from all sides.

Such a change of strategy would probably satisfy scientists who warn that protection of the world's largest remaining humid forest is crucial because it helps regulate the global climate, retains the soil and watershed and is the largest store of known and unknown plant and animal life.

Approved by Timber Group

The project was approved this week by the International Tropical Timber Organization, a new body that for the first time brings together countries that produce and consume tropical hardwood trees. The 42-nation organization ended a 10-day conference here on Friday.

The rapid depletion of the earth's tropical timber was the thread that ran through all the debates, even though the organization is a trading group. For both the timber industry and the owners of the forests, trade worth $6 billion a year is at stake.

The group also approved a plan to select and market lesser known tropical species to preserve the popular and ever-scarcer hardwood trees. Some funds went to other, small pilot projects to farm the forest while protecting it.

The new Brazilian plan is the most ambitious of its kind. It will begin in September, when technicians start working on a thorough inventory of all usable species in a portion of the Antimari Forest, a 247,000-acre reserve in the state of Acre.

In successive stages they will study the rate and quantity at which forest products can be responsibly exploited or replanted and finally create companies to handle them. The forest yields Brazil nuts, resin, rubber and medicinal plants and has some of Brazil's last remaining mahogany.

Frontier Area Changing

The state of Acre was picked because it has only 350,000 people and 95 percent of its forest cover is still intact. But this frontier state is quickly changing as a new target of investors and settlers.

"We think the Acre project could be a watershed decision toward conservation of the tropical forest," said Adam Markham, an official of the World Wildlife Fund. John Medeiros, the head of the United States delegation, called the plan "superlative."

Similar enthusiastic support for the project by the biologists, economists and timber merchants here is widely seen as a sign of how, in many quarters, traditional thinking about the rain forest has made an about-face.

For centuries, logging in the tropics has been strictly a predatory practice and even today, conservationists say, tropical plantations are small and replanting is rare; less than one tree replaces every 20 felled. Japan, the single largest importer of tropical timber, on Friday pledged $2 million that made the start of the project possible.

Reversal by U.N. Agency

Officials of the United Nations Food and Agricultural Organization, who a decade ago argued that "forest management" in the tropics made no economic sense, have now also reversed their views. And even conservationists have adopted the notion that managing the forest is more realistic than their dream of putting the jungle off-limits in regions populated by the poor.

Delegates here have called the Timber Conference the most important political forum for dealing with tropical forest issues, but the meetings of the last week also underline the wide gap between the poor nations that own the jungles and the rich that buy the wood.

The poor complained that the rich controlled the market and the industrialization of wood and kept wood prices low through stockpiling. The rich argued that the poor should become better organized, meet delivery deadlines and quality needs and enforce their laws that protect their forests.

In the corridors, where representatives from international conservation groups and timber concerns took turns lobbying, timber traders took great pains to convey that cattle ranchers and settlers destroyed most of the world's dwindling forests. Only 7 percent of the trees cut are used for export, they said.

New York Times
July [illegible], 1988
Section 1, p. [illegible]

© 1988 The New York Times. Reproduced by the Library of Congress,
Congressional Research Service with permission of copyright claimant

IMPACTS OF GLOBAL CLIMATE CHANGE ON FORESTS AND ROLE OF FORESTS IN MITIGATING CLIMATE CHANGE

(By Adela Backiel, Specialist in Natural Resources Policy, Congressional Research Service)

Besides contributing to the phenomenon of global climate change, forests and forest productivity, particularly those in temperate zones, are likely to be affected by changes in our climate. The following readings describe how temperate forests may be affected ecologically and physiologically, how increased forest growth could help ameliorate the increased CO_2, and how the management of our domestic forests could be changed, in part to accommodate any effects of global climate change. Anticipating, assessing, tracking and managing these impacts is a primary area of potential policy exploration regarding forests and the practice of forestry in the United States.

The results of six case studies conducted by the Environmental Protection Agency (EPA) are summarized in the forestry chapter of the draft report "The Potential Effects of Global Climate Change on the United States." These studies indicate that the natural forests of the United States would be significantly affected by climate changes. The effects could include shifts in ranges of tree species and forest ecosystems, forest productivity changes (both increases and decreases), and related effects such as changes in biological diversity, water retention, wildlife habitat, and potential regional disturbances such as increased breakouts of forest pests, or disease. Needs for further research are also described.

Forests in the United States do not just need to accommodate the effects of global climate change. As discussed in the reading by Sandenburgh, Taylor and Hoffman, how forests adjust to the effects of global warming will also depend on changes in forest management and planning. Controlled studies have shown that higher levels of carbon dioxide have the potential to increase plant productivity. Considering the complexity of forest ecosystems and the linkages between soil, water, climate and tree physiology, extrapolating the results of such controlled experiments to what will happen in actual forests is very controversial. But if increased productivity were actually to occur, appropriate changes in forest management directions could help capitalize on potential increases in productivity to help utilize the increased levels of CO_2.

Further discussion of how higher levels of carbon dioxide might or might not increase plant productivity is the theme of the review by Kramer and Sionit. These authors make clear that other environmental factors may make greater differences in tree growth than CO_2 will. The net effects appear to be the result of complex interactions among many factors, and many of the factors and interactions are not well understood.

In his testimony, Moomaw identifies a number of forest management policies which would encourage use of trees as storehouses of sequestered carbon on both public and private U.S. lands. One such policy would be to make carbon fixation one of the multiple purposes for which national forests are managed. Others include linking CO_2-emitting projects with offsetting forestry projects and trees in urban settings to reduce air-conditioning requirements.

"Climate and Forests," by Sedjo and Solomon, after reviewing forests as sources and sinks of carbon dioxide, discusses the economics of forest management, how much land would be needed for carbon uptake, and whether such expanded forestry would be economically viable. They conclude that significant expansion of tropical plantations could be economically feasible, provided that appropriate financial incentives were to be created, and that the wood might find markets in electricity generation and in housing and other industrial uses. The extent of the needed subsidy would be, they say, an important researchable question.

One important factor in both the capacity and economics of forest use to mitigate global warming is the extent to which tree growth rates might be accelerated through species selection and cultivation practices. This factor is discussed to some extent in all of these readings, and is treated in the Marland paper in the previous section as well. More work has been done in cultivation practices than in species selection or development, but there is some evidence that casting the research net over a wider variety of species, coupled with biogenetics, would be a potentially fruitful area of research.

The final forestry reading focuses on the two primary commercial timber regions, the West and the South from the perspective of industrial capacity and effects. While pointing out the uncertainties surrounding the identification of impacts that climate changes might have on forests, Regens, Cubbage, and Hodges also describe some actions and positions that are likely to be taken by the forest industry, which leads to a discussion of possible governmental action.

THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES

DRAFT

REPORT TO CONGRESS

Volume 2: National Studies

Editors: Joel B. Smith and Dennis A. Tirpak

United States Environmental Protection Agency
Office of Policy, Planning, and Evaluation
Office of Research and Development

October, 1988

DRAFT

CHAPTER 11

THE POTENTIAL IMPACT OF RAPID CLIMATIC CHANGE ON FORESTS IN THE UNITED STATES

FINDINGS

Global warming could significantly affect the forests of the United States. Changes could be apparent in 30 to 80 years, depending upon the region, a site's quality, and the rate of climate change. There may be northward shifts in species ranges, dieback along the southern reaches of species ranges, and changes in forest productivity. The combined effects of climate change and other stresses may exacerbate these impacts. Different migration rates and climate sensitivities may result in changes in forest composition. Large reductions in the land area of healthy forests are probable during this century of adjustment to climatic changes.

Range Shifts

- The southern ranges of many forest species in the eastern United States could dieback as a result of higher temperatures and drier soils. The southern boundary could move several hundred to one thousand kilometers (up to six hundred miles) in a generally northward direction for the scenarios studied.
- The potential northern range of forests species in the eastern U.S. could shift northward as much as 600-700 km (370-430 mi) over the next century. Actual northward migration could be limited to as little as 100 km (60 mi), due to the slow rates of migration of forest species. It could take centuries for eastern forests to fully migrate to potential northern distributions. If climatic change is too fast, some tree species may not be able to form healthy seeds, thus halting migration.
- If elevated CO_2 concentrations substantially increase the water-use efficiency of tree species, the southern declines could be alleviated.
- If climate stabilizes, forests might eventually regain a generally healthy status (over a period of several centuries). In the meantime, declining forests could be subject to increased fires, pest attacks, and replacement with low-value trees, grasslands, and shrubs.

Productivity Changes

- Dieback along the southern limits of distribution of many species could result in productivity declines of 46 to 100

Productivity Changes

- Dieback along the southern limits of distribution of many species could result in productivity declines of 46 to 100 percent, depending on how dry soils become.
- Productivity could increase along the northern limits of some eastern tree species, particularly as slow-growing conifers are replaced by more rapidly growing hardwoods.

Combined Impacts with Other Stresses

- Large regions of severely stressed forests, combined with possible increases in fires, pests, disease outbreaks, wind damage, and air pollution could produce major regional disturbances. These factors were not considered for this study.
- Additional impacts of changes in forests include reductions in biotic diversity, increased soil runoff and soil erosion reduced aquifer recharge, changes in recreation, and changes in wildlife habitat.

Policy Implications

- Institutions such as the U.S. Forest Service, state forest agencies, and private companies should begin to consider how to factor climate change in their long-term planning. Global climate change may need to be a factor in the Forest Service's 50-year plan.
- Strategies that forest agencies may wish to consider include the feasibility of massive reforestation on a much larger scale than practiced now, and the possible introduction of subtropical species into the Southeast in order to maintain U.S. forest productivity. A coordinated public and private reforestation effort, together with development of new and adapted silvicultural practices, may be required. A large reforestation program would also reduce atmospheric CO_2 concentrations, slowing the rate of global warming.

EXTENT AND VALUE OF U.S. FORESTS

Forests occupy 33% of the U.S. land area and exist on some lands in all 50 States. In total, they occupy 299 million hectares (738 million acres) and are rich in such resources as water and wildlife.

Chapter 11

Many biotic and abiotic factors influence the condition of forests, but climate is the dominant factor (Spurr and Barnes, 1980). This chapter summarizes what is currently known and predicted regarding the effects of rapid climatic change on U.S. forests.

Distribution and Ownership

Eight major forest regions of the conterminous 48 States contain 84% of the forested ecosystems of the United States (Figure 11-1). The forested areas of Alaska and Hawaii represent the remaining 16% (Table 11-1). Each forest region includes one or more forest types distinguished by the major tree species present. As a general rule, some types in each region have predominantly coniferous tree species (i.e., evergreen, needle-leaved, and softwoods); other forest types are composed mostly of deciduous trees (i.e., tree species that are broad-leaved, have no winter foliage, and are hardwoods). Forest types with a mix of coniferous and deciduous trees, however, are not uncommon.

Superimposed over the natural distributions of trees, forests, and ecosystems in the United States is the human infrastructure. Ownerships include Federal, State, and private lands (Table 11-1). In broad terms, the United States contains public forests (28%), private industry lands (14%), and many small private forests or woodlands (58%) that mostly consist of parcels less than 200 hectares (ha) (about 500 acres) (Woodman, this report). The Federal Government ownership of 40 million ha (99 million acres) of commercial forest lands is primarily in the National Forest System managed by the U.S. Department of Agriculture's Forest Service (36 million ha or 91 million acres); most of the remainder is managed by the Department of Interior's Park Service, Fish and Wildlife Service, or Bureaus of Land Management and Indian Affairs. State ownerships total 9 million ha (23 million acres). Private lands are divided between those of industrial forest companies (27 million ha or 68 million acres) and small landowners, who collectively have 112 million ha (277 acres).

To the degree that all forest lands are owned by some individual or organization, all forest lands are under some form of management. A continuum of management policies exists, ranging from those lands intended to have minimal human intervention, except for protection from catastrophic wildfire (e.g., some parks and most wilderness areas), to lands where silvicultural practices are intensively applied (e.g., the most productive Federal, State, and industrial forest lands dedicated to growing tree crops, Table 11-2). The forests under government and industrial management constitute roughly one-fourth of the

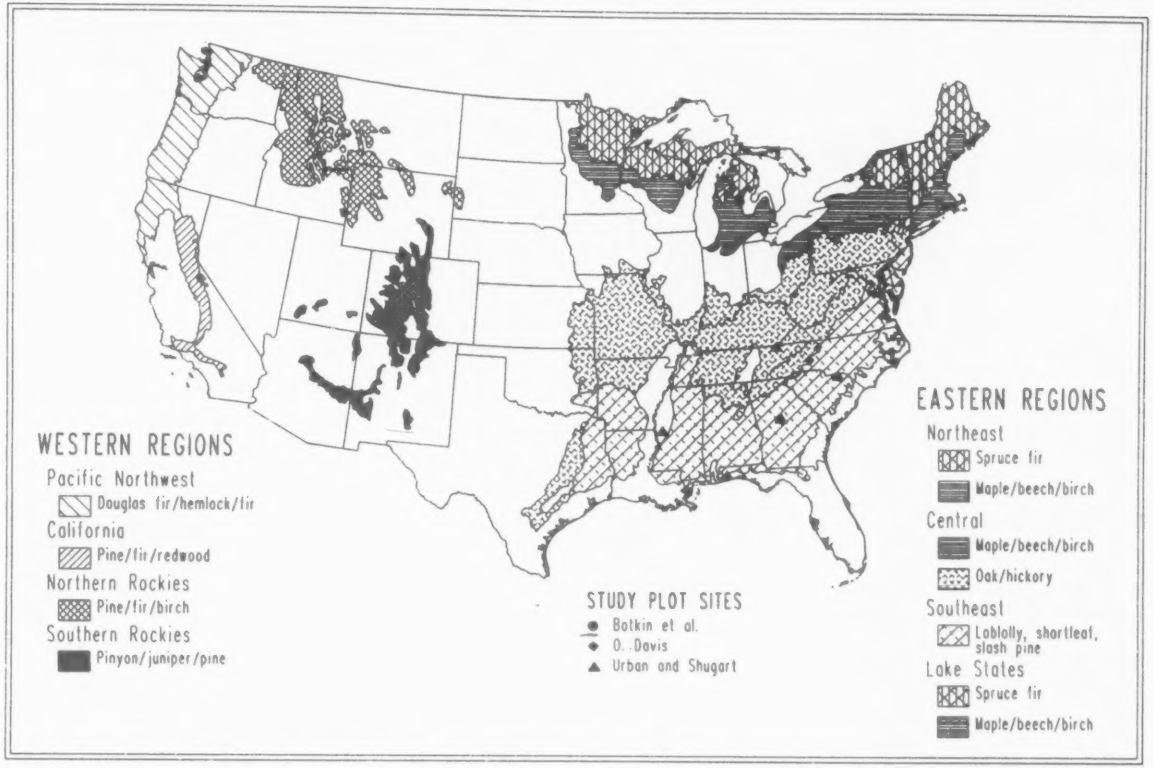

WESTERN REGIONS
Pacific Northwest
Douglas fir/hemlock/fir
California
Pine/fir/redwood
Northern Rockies
Pine/fir/birch
Southern Rockies
Pinyon/juniper/pine
STUDY PLOT SITES
Botkin et al.
O. Davis
Urban and Shugart
EASTERN REGIONS
Northeast
Spruce fir
Maple/beech/birch
Central
Maple/beech/birch
Oak/hickory
Southeast
Loblolly, shortleaf, slash pine
Lake States
Spruce fir
Maple/beech/birch

Figure 11-1. Major Forest Regions of the Conterminous United States and Their Primary Tree Groups

Table 11-1. Area of U.S. forest lands in 1977 by federal, state, private, and other ownerships (millions of hectares[1]; USDA, 1982).

			Commercial Forests[2]						
					Private				
	Region/States	Primary Tree Species	Federal	State	Industry	Non-Indus	Others[3]	Total	% Total
EAST	Northeast - CT, MA, ME, NH, RI, VT	spruce-fir maple-beech-birch	0.3	0.4	3.9	7.8	0.7	13.1	4.4
	Lake States - MI, MN, WI, ND, SD(E)	spruce-fir maple-beech-birch	2.3	2.8	1.7	9.9	4.2	20.9	7.0
	Central - DE, IA, IL, IN, KA, KY, MD, MO, NB, NJ, OH, PA, TN, WV	maple-beech-birch oak-hickory	1.8	2.0	8.6	22.9	2.6	37.9	12.7
	Southeast - AL, AR, FL, GA, LA, MS, NC, OK, SC, TN, TX, VA	loblolly, shortleaf slash pine	5.8	1.0	14.7	54.3	8.0	83.8	28.1
WEST	Northern Rockies - ID, MT, SD(W), WY	pine-fir-birch	9.1	0.6	0.8	2.7	9.3	22.5	7.6
	Southern Rockies - AZ, CO, NM, NV, UT	pinyon-juniper-pine	6.4	0.3	0.0	2.4	24.1	33.2	11.1
	Pacific Northwest - OR, WA	D. fir-hemlock-fir	7.8	1.2	4.0	3.2	5.3	21.5	7.2
	California - CA	pine-fir-redwood	3.4	.03	1.1	2.0	9.8	16.3	5.4
SEPARATE STATES	Alaska - AK	spruce-hemlock-hardwood	3.3	1.0	0.0	0.1	43.9	48.3	16.2
	Hawaii - HI	ohia	.01	0.2	0.0	0.2	0.4	0.8	0.3
		TOTAL	40.2	9.5	34.8	105.5	108.3	298.3	100
		% TOTAL	13.5	3.1	11.7	35.4	36.3	100	

---

[1] Hectare x 2.47 = acres

[2] Commercial forests are those capable of growing at least 1.4 m^3/ha/yr (20 ft^3/ac/yr) of industrial wood materials.

[3] Other forests include county and municiple forests and those federal lands withdrawn from industrial and wood production for use as parks, preserves, and wilderness.

Source: USDA (1982).

Table 11-2. Percentage of Forest Lands by Level of Management Within Four U.S. Regions. (Estimates for 1977

U.S. Region	% Forest Plantations[a]	% Other Commercial[b]	% Reserved/ Deferred[c]
East			
North	9	80	11
South	21	69	10
West			
Rocky Mountains	2	38	60
Pacific Coast	16	44	40

[a] Intensively managed plantations.
[b] Moderately managed forests.
[c] Other commercial.

Source: USDA (1982).

total and might be the easiest to manage under climatic impacts simply because they are larger blocks of lands already under strong management commitments.

Value of U.S. Forests

Most populated regions in the United States are located close to or within a forested region. For instance, the Boston-Washington corridor is within the eastern hardwoods. Atlanta and Southeast populations are interspersed among the southern pine forests. Chicago and nearby Great Lakes communities are surrounded by the mixed conifer-hardwood forests of that region, and the Los Angeles to San Francisco populations parallel the Sierra Nevadas to the east. Forests, therefore, are part of the environmental fabric and general habitability for the majority of U.S. citizens.

All forests shed water to some degree, and two-thirds of the water runoff in the contiguous 48 States comes from forested ecosystems. Precipitation passes through forested ecosystems as canopy throughfall and flows in or along tree stems, the ground surface, and the soil; eventually, some precipitation flows into streams. Water yields from U.S. forests provide about 750 billion liters (200 billion gallons) of water per day for major uses such as irrigation (47%), steam electric (26%), manufacturing (15%), and domestic use (6%). These levels of demand are projected to continue to the year 2030 (USDA, 1981).

A favorite use of forests is outdoor recreation. Activities include hiking, camping, hunting, sightseeing, boating, swimming, fishing, skiing, sledding, and snowmobiling. A 1977 survey of U.S. households indicated that a majority of people participated in outdoor recreation four or more times per year (USDA, 1981).

About 190 million ha (470 million acres), or 64% of the total U.S. forested ecosystems, are highly productive commercial forest lands. These lands represent about 10% of the world's forest area, but they supplied nearly a quarter of the world's industrial forest products in the late 1970s (USDA, 1982). In 1980, 1.7 million people were employed in timber-based occupations across the United States. Such employment is basic to the economic well-being of many small towns and communities (Schallau, 1988). The total value of timber products harvested in 1972 was about $6.4 billion, and the total value after such processes as manufacturing, marketing, transport, and construction amounted to $48 billion, or 4% of the nation's gross national product. In 1979, timber product exports and imports were valued at $7 and 9 billion, respectively. Looking ahead, the consumption of wood products in the United States is projected to increase between current levels and the year 2030 (USDA, 1982).

RELATIONSHIP BETWEEN FORESTS AND CLIMATE

Scientific understanding of forest ecosystems has greatly advanced with each decade of this century. Yet the literature contains little information concerning the direct or indirect effects of climate change on the complex of biological and physical processes in forest ecosystems. Some insights are gained from paleobotanical studies regarding past rates and magnitudes of change during glacial-interglacial cycles, as well as changes in forest composition. Similarly, observations of forest responses to unusual drought or other weather extremes provide some knowledge. Estimates of rate, magnitude, and quality of change have also been derived using computer models developed by plant ecologists or forest management scientists for other objectives. Their validation for understanding how a forest can adapt to climatic change is only in the initial stages.

Climate is a primary determinant of existing forests. The ranges of annual average temperature and rainfall variation determine global forest distributions relative to different biotic regions (Figure 11-2). Substantial increases in temperature or decreases in rainfall could, for example, produce a shift from a forest to a grassland type. Thus, accelerated climatic change resulting from human activities and related effects on U.S. forests is of high concern to citizens and policymakers alike.

Magnitude

As pointed out by Spurr and Barnes (1980), there is ". . . irrefutable evidence that vegetation (i.e., ecosystems) has been in an almost constant state of instability and adjustment due to an almost constantly changing climate over the past 10,000 years and even over the past several hundred years . . . ." Lines of evidence come from studies of fossils, tree rings, carbon-14 dating, plus peat and pollen analyses (Barbour et al., 1987).

Historical climatic changes appear to have been associated with such phenomena as fluctuations in solar radiation, earth orbit variations, and volcanic activity. Evidence of repeated continental glacial advances and contractions in the Northern

Hemisphere dramatically illustrates the large-scale effects of global climatic change.

In response to the glaciation, ecosystems shifted south. Evidence from fossil pollen, for example, indicates a southward shift of spruce into Georgia and east Texas during the last glacial advance and treeless tundra in the Great Lakes States (Spurr and Barnes, 1980). During the maximum interglacial warmth of 6,000 to Figure 11-2. Approximate Distributions of the Major World Bioass Based Upon Mean Annual Temperature and Precipitation (Hammond, 1972) 9,000 years ago, which was 1.5°C (2.7°F) warmer than the present temperature level, plant zones were one to several hundred km (60-250 miles) north of present distributions.

Rates

All forested ecosystems experience change on both spatial and temporal scales; each biological and physical forest component may respond to climatic variation on different spatial and temporal scales. For example, microorganisms, insects, and birds come and go with relatively short-term climatic variation; shrub species abundances vary within the timespan of decades; trees, once established, could persist for centuries. This understanding is important from the perspective of climatic change, since it implies that forested ecosystems do not respond as a unit, but in terms of parts. Different parts respond differently; consequently, future forested ecosystems under a rapidly changing climate could be quite different from those existing today.

At the expected rapid rate of climatic change, the potential rates of forest migration would become a major concern. Migration rates vary by species. Paleorecords of the Holocene (10,000 years ago to present) show that extension of ranges for tree species of eastern North American (in response to glacial retreat) varied from 10 to 20 km (6 to 12 miles) per century for chestnut, beech, maple, and balsam fir (Zabinski and Davis, this report). Other species within the oak and pine groups extended at faster rates, i.e., 30 to 40 km (19 to 25 miles) per century.

Mechanisms

Knowledge of causal links between weather patterns and forest response is fundamental to projecting growth and composition effects resulting from climate change. Another requirement is to understand the climatic influences on population processes of forest plants and animals. These include such phenomena as fires, windstorms, landslides, pest outbreaks, and other disturbances that affect survival and subsequent colonization by different species. Furthermore, the processes that control the dispersal of seeds through a mosaic of different ecosystem types (such as forest patches interspersed with agricultural lands, wetlands, grasslands, and other land-use groups) must be clearly defined.

Among the important factors now known to influence the growth and distribution of forests are the following.

Temperature

The optimum temperature for growth depends upon the tree species and other conditions. Warmer temperatures usually increase the growth of plants. However, very high temperatures decrease the growth of plants or kill those growing at optimum (or higher) temperatures. Cold temperatures can limit plant distributions by simply limiting growth at critical stages or by directly killing plants.

Precipitation

Too much or too little precipitation can limit forest production and survival. Too much rainfall in some areas can cause flooding or raise the water table, thus drowning roots that require oxygen or promoting fungal attack. Too little rainfall can reduce growth, cause susceptibility to fire or pestilence, and possibly kill plants. The seasonal timing of rainfall is more important than total annual rainfall, although forests also require some minimum total annual rainfall (see Figure 11-2).

CO_2 Concentration

High CO_2 concentrations could increase tree growth through increases in photosynthesis rates and water-use efficiency (primarily hardwood species) when water and other nutrients are not limited (Strain and Cure, 1985). Plant responses to CO_2 have been investigated largely in growth chambers and are difficult to extrapolate to the real world. Responses are varied and do indicate some measure of adaptive capability most likely imparted from ancestral exposure to much higher and lower levels in the geologic past. However, in natural situations, water nutrients or temperature usually are limiting factors in forest growth, thus making the impacts of CO_2 enrichment uncertain. If water use efficiency increases, then tolerance to drought might increase, ameliorating declines in southern parts of ranges. Unfortunately, the current state of knowledge does not allow generalizations on this subject.

Light

The amount of sunlight bathing an ecosystem sets the upper limit on net primary productivity. Thus, the tropics exhibit higher productivity than do the boreal regions. This potential productivity would, of course, be limited by other climatic effects such as drought, cold, heat, and natural disturbances, and the time required for forests to shift into new ranges. The length of day exerts considerable control on physiological processes such as release from and onset of dormancy. Significant northward shifts of forests would alter their day length regime, producing uncertain results.

Nutrient Status

In addition to climate, most forest growth is strongly influenced by availability of soil nutrients. Disturbances over vast regions, such as by drought followed by fire, can release large quantities of essential nutrients into the atmosphere and surface waters and can make soils deficient. Lengthy periods of soil development are usually required to replenish the soil nutrients before a large, mature forest stand can be supported. In turn, soils reflect properties of the forests that they support. This results from decades of nutrient uptake, litterfall, decomposition, and other processes.

Atmospheric Chemistry

Much of the nutrient budget of forests involves deposition of chemicals from the atmosphere as gases, aerosols, particles, and in solution. Although most of these act as nutrients, some produce acid deposition that can leach important soil nutrients (e.g., $SO_4^{=}$), produce a fertilizing effect (e.g., NO_3^{-}), or damage leaf tissue (e.g., O_3). Climatic change will alter transport paths of air pollutants, and increased temperature could increase the rates at which gases convert to deleterious forms.

Disturbances

Almost continually, forests experience natural disturbances or stresses from biotic or abiotic agents alone or in combination. Examples are insects and disease outbreaks, plant competition, wildfire, drought, cold extremes, and windstorms.

These disturbances, which are among the primary factors controlling the successional processes in forests (Pickett and White, 1985), may range from an opening of small gaps in the canopy as the result of single tree death or of windthrow occurring when trees are blown down by heavy winds (predominant successional mechanisms in eastern hardwoods), to large clearings from fire, windthrow, or pestilence (predominant successional mechanisms in western forests).

Landscape Processes

The horizontal movement of material and disturbances through the landscape is critical to the processes controlling forest migration, species diversity in forests, and the spread of fire, windthrow, and pestilence effects. These processes are very poorly understood; quantification in the emerging field of landscape ecology is just beginning.

Multiple Stresses

In general, trees or forests stressed by one factor, e.g., accelerated climatic change, are more susceptible to natural stresses (secondary disturbances) such as insects, disease, or invading weed species. The concept of multiple stresses leading to forest declines is becoming more widely recognized (Manion, 1981). Regional climatic changes, even if temporary, frequently predispose forests to damage by other natural or anthropogenic stresses.

PREVIOUS STUDIES ON THE NATIONAL EFFECTS OF CLIMATIC CHANGE ON FORESTS

Concern regarding effects of climatic change on U.S. forests has prompted several excellent reviews. One of the most comprehensive (Shands and Hoffman, 1987) was the result of a conference sponsored by EPA, the National Forest Products Association, and the Society of American Foresters. While pointing out the high uncertainty associated with current predictions of climatic change, several authors suggested that if predictions are true, distributions of key forest species in the United States will change significantly.

Other recently produced compilations broadly consider forest effects, such as in agriculture, prairie land, and the Great Lakes (White, 1985; Titus, 1986; Meo, 1987; Tirpak, 1987). These reviews are largely pioneering efforts and some overlap occurs, but each presents some key points.

The methods used in the previous studies are quite similar to those used in this report. They include computer modeling of forest processes, literature surveys, studies of fossil evidence, and empirical relationships constructed by experts. The estimates of future change produced from these studies are generally based on the output of one or more of the General Circulation Models used for this report. Thus, the results of the previous studies are consistent with those reported here.

STUDIES IN THIS REPORT

Six studies on forest effects contributed to the regional case studies reported in this volume. The purpose was to use existing methods and data bases to protect U.S. forests from predicted climatic change. The selection of the six studies was based upon three criteria: use of available technology; testing hypotheses focusing on causal mechanisms; and a mix of studies that complemented each other, such that the strengths in one approach might overcome the weaknesses of another.

This report focuses primarily on forests within the lower 48 States. It is worth noting, however, that the largest magnitude of warming is expected in the northern latitudes encompassing the boreal forest and other forest types in Alaska and Canada. These large forests could be under significant risk from climatic warming.

Study Design

Characteristics of the six studies are briefly listed in Table 11-3. With the exceptions of the Overpeck and Bartlein study and the Woodman study, the methods are discussed in the regional case study chapters and will be mentioned only briefly here.

Two studies used correlations between tree distributions and climate (Overpeck and Bartlein; Zabinski and Davis). Overpeck and Bartlein's approach consists of correlating the modern pollen distributions of important tree species with January and July mean temperature and annual rainfall. The correlation is then tested by reconstructing past pollen distributions from General Circulation Model simulations of past climates (during the most recent glacial-interglacial cycle) for each species and comparing them to observed pollen distributions from those periods. Future pollen distributions are then constructed from the expected doubled CO_2 climate projected from the different model climate scenarios. The correlations are constructed on modern pollen distributions, rather than tree distributions, to allow the direct comparison to fossil pollen data. Modern pollen distributions are similar to, but not exactly the same as, modern

Table 11-4. Principal Investigators, Regional Focus and Method of Approach for the Regional Forested Ecosystem Studies

Principal Investigator	Region	Method
Overpeck and Bartlein	Eastern North America	Correlation and fossil studies
Urban and Shugart	Southeast Uplands	Forest dynamics model
Botkin et al.	Great Lakes	Forest dynamics model
Zabinski and M. Davis	Great Lakes	Correlation
Davis	California	Fossil studies
Woodman	Southeast, California, and National	Literature review

tree distributions. The verification studies indicate that the approach works reasonably well at a coarse spatial resolution. That is, northern trees are in the north and southern trees are in the south, with the regional patterns being reasonably well represented.

The approach of Zabinski and Davis is essentially the same as that of Overpeck and Bartlein, except that the correlations are constructed from the actual modern tree distributions rather than from the modern pollen distributions (see the Great Lakes chapter of this report).

Two of the studies used computer models of forest dynamics (Botkin et al.; Urban and Shugart). Both studies explored forest response on a range of soil types from well drained to poorly drained. Forest growth simulations from bare ground represent conditions after a fire, logging, or similar disturbance. Mature stand simulations are useful for investigating the potential response of present forests to gradual climatic change in the immediate future.

For the California case study, Davis reconstructed vegetation patterns in the Sierra Nevadas from fossil pollen studies for the interglacial warm periods between about 6,000 and 9,000 years ago. These reconstructions represent possible analogs of a future warm period at the lower magnitude of the predicted future warming.

A literature review was conducted by Woodman for the Southeast and California forested regions and peripherally for the nation as a whole. The purpose was to ascertain the attributes of the forest resource in terms of extent, ownership, economic and recreational value, and policy considerations.

Study Results

The six studies conducted by EPA are consistent enough to indicate that climatic changes would significantly affect the natural forests of the United States. The distribution of healthy forests in the eastern United States appears to become greatly reduced from their areas during the next century (see Figure 11-3 and 11-4). This results from a very slow northward migration coupled with a fairly rapid decline in the southern and western parts of species ranges. Drier forest conditions in the United States, induced as much by increased temperature as by changes in rainfall, would mean less tree growth and therefore reduced forest productivity in general.

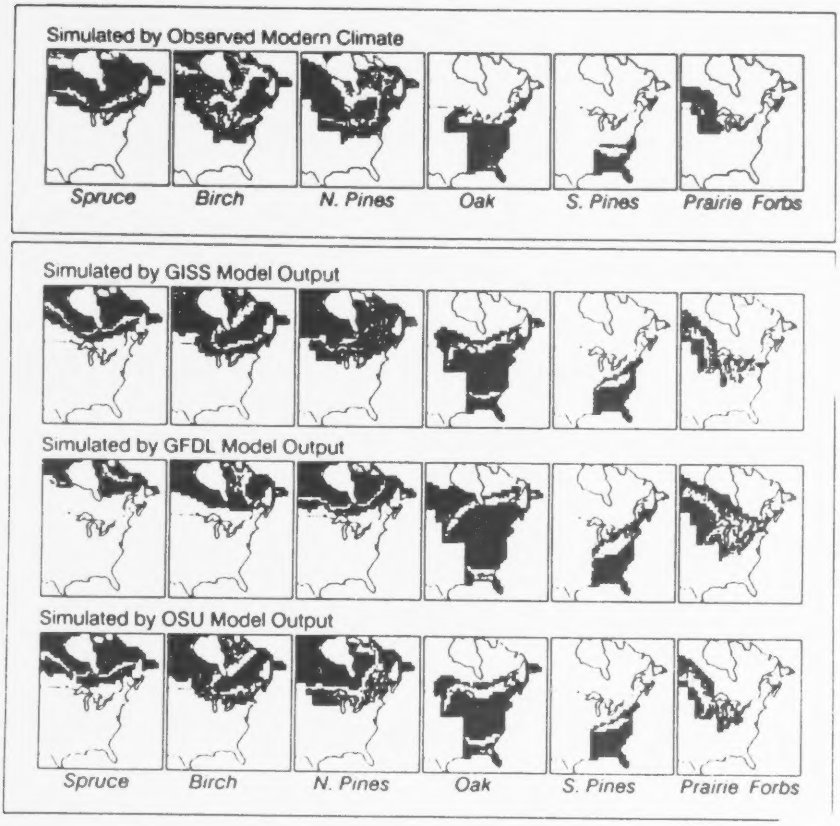

Simulated by Observed Modern Climate
Spruce
Birch
N. Pines
Oak
S. Pines
Prairie Forbs
Simulated by GISS Model Output
Simulated by GFDL Model Output
Simulated by OSU Model Output
Spruce
Birch
N. Pines
Oak
S. Pines
Prairie Forbs

Figure 11-3. Present distribution of major forest genera and herbs vegetation of eastern N. America compared to potential future distributions after reaching euilibrium with the climate predicted for $2xCO_2$. The comparison is based upon simulated modern pollen data (a) and simulated future pollen abundances for each of the three $2xCO_2$ scenarios: (b) GISS; (c) GFDL; and (d) OSU (Overpeck and Bartlein, Volume _).

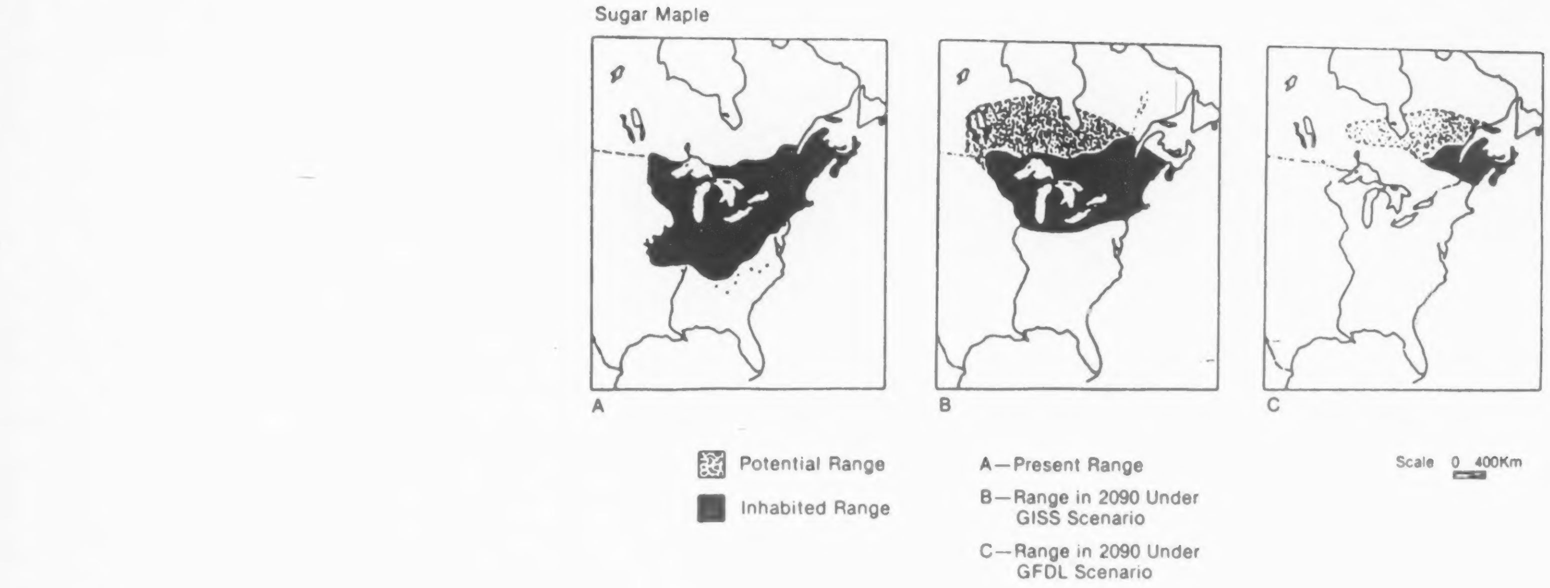

Sugar Maple
A
B
C
▨ Potential Range
■ Inhabited Range
A—Present Range
B—Range in 2090 Under GISS Scenario
C—Range in 2090 Under GFDL Scenario
Scale 0 400Km

Figure 11-4. Present and future geographical range for sugar maple. a: Present range. b: $2XCO_2$ climate-space in 2090 A.D. under the GISS scenario. Black area is the predicted species range; stippled area is potential range. c: $2XCO_2$ climate-space in 2090 A.D. under the GFDL scenario. Black area is the predicted species range, stippled area is potential range (Zabinski and Davis, Volume _).

The forest simulation models provide an indication of the importance of uncertainties imparted by the climate scenarios. The climate scenarios differ primarily in their representation of regional rainfall patterns. The model results indicate that temperature has a large effect on forest health, either directly through cold and heat stress or indirectly by exaggerating drought effects. Thus, the overall characteristics of forest responses are remarkably similar among the three climate scenarios.

Magnitude

Eastern Forests - Northern Limits

All of the study results suggest a northward expansion of most eastern tree species (Figure __ displays results from Overpeck and Bartlein). That is, spruce, northern pine, and northern hardwood species would move north by about 600-700 km (375-440 miles) into the Hudson Bay region of the Canadian boreal forest (Overpeck and Bartlein; Zabinski and Davis). New England coniferous forests would be replaced by more hardwood forests and especially by the oak species from the eastern mid-United States (Botkin et al.; Overpeck and Bartlein; Zabinski and Davis). As the northern mixed forests shift from spruce-fir to sugar maple, some sites could actually triple their present productivity (Botkin et al.).

Additionally, southern pine species could shift about 500 km (310 miles) into the present hardwood forest lands of eastern Pennsylvania and New Jersey (Overpeck and Bartlein; Urban and Shugart; Solomon, 1986; Miller et al., 1987). Depending upon the severity of climate change, Urban and Shugart estimate that near the northern limits of slash pine in East Tennessee, above-ground woody biomass in 100 years could range from little change to extremely low biomass with no trees supported (i.e., a grassland, savanna, or scrub). However, even with little decrease in productivity, species shifts would alter the forest composition from shortleaf to loblolly pine, a more commercially valuable tree species.

Eastern Forests - Southern Limits

Ultimately, forest decline and mortality could truncate southern distributions of tree species by as much as 1,000 km (625 miles) in many northern hardwood species (Zabinski and Davis; Overpeck and Bartlein) or by as little as a few hundred km (60 miles) in southern pines and hardwoods (Urban and Shugart; Solomon and West, 1986). Under the driest scenario, Zabinski and

Davis predict local extinction in the Great Lakes region of many eastern tree species such as eastern hemlock and sugar maple (Figures 11-3 and 4). These estimates bear considerable uncertainty for all species.

These uncertainties are particularly true for the southern limits of southeastern species that border the continental margin. The actual southern climatic limitations of these species are not well known (Urban and Shugart). Nevertheless, under the most severe climate scenario in the Southeast with increased temperatures and decreased growing-season precipitation, Urban and Shugart's results suggest that the 18 tree species they considered would no longer grow in the southern half of the region. Present forest lands in the region would be replaced by scrub, savanna, or sparse forest conditions. Under the most mild scenario, much of the southern half of the Southeast would not support trees, and areas in South Carolina would be marginal, supporting about half the current biomass of forest.

Biomass accumulations in 100 years for mature natural forests in productive sites in the Lake States could be reduced to 23-54% of their present values (Botkin et al.; Solomon and West, 1986). On poor sites, forests could be converted to grassland or savanna with very low productivity, ranging from 0.4 to 28% of their present values.

Western Forests

Similar projections were made for six western coniferous species: ponderosa and lodgepole pine, Douglas-fir, western hemlock, western larch, and Englemann spruce (Leverenz and Lev, 1987). Predictions are mixed for the West. Because of the mountainous conditions in the West, upslope shifts are possible for Douglas-fir, ponderosa, and western hemlock in the northern Rocky Mountains. In the coastal mountains of California and Oregon, Douglas-fir should shrink in the lowlands and be replaced by western pine species (Davis, this volume; Leverenz and Lev, 1987). Overall, the western forest lands are predicted to favor more drought-tolerant tree species, such as the hard pine group, at the expense of fir, hemlock, larch, and spruce species.

If regional drought persisted, the frequency of fires could increase, significantly reducing total forested area. Also, with massive upslope movement, some species would be pushed off the tops of mountains into local extinction.

No quantitative estimates have been derived for productivity for the western forests under potential warming conditions. However, using the analog approach of Davis, under the most severe conditions projected for California, the species composition of the west-side Sierra Nevada forests would become more similar to that of the east-side forests. This would reduce the standing biomass to about 60% of current levels.

Rates of Decline and Migration

In the Great Lakes region, significant forest decline and forest compositional change could become evident within 30 to 60 years. In the Southeast region, forest declines could become evident in 60 to 70 years, with declines in the drier western portions occurring even earlier, perhaps in about 30 years (Figure 11-5) (Urban and Shugart).

These rapid declines, coupled with the expected magnitude of change, raise the question of how fast forests can migrate. Based upon fossil records, Zabinski and Davis have estimated that the maximum dispersal rate of several tree species in response to the last glacial retreat was roughly 50 km (30 miles) per century. Under the expected rapid warming, they estimated that a dispersal rate of about 100 km (600 miles) per century would be required to maintain species distributions near their current extent. Such migration routes are doubtful, suggesting greater reductions in species ranges under rapid climatic changes.

Mechanisms of Migration

Distribution changes suggested by these studies (i.e., migrations) must be considered carefully. Reproductive processes are essential for the migration of tree species across the landscape. For many tree species, climatic change could reduce natural regeneration in an existing location and introduce the species at different latitudes or altitudes. Reproductive processes in trees, such as flowering, pollination, seed set, seed germination, and seedling competitive success, are particularly sensitive to climate.

Specific regional climate scenarios vary as a function of the GCM. All scenarios predict increases in temperature; however, some predict increases in rainfall, and others predict decreases. The northward shifts of species appear to result from a release from cold temperature stress, which normally freezes flowers, seedlings, and even adult trees. However, the western and southern limits of eastern tree species appear to result from insufficient moisture stress and excessive heat stress, which

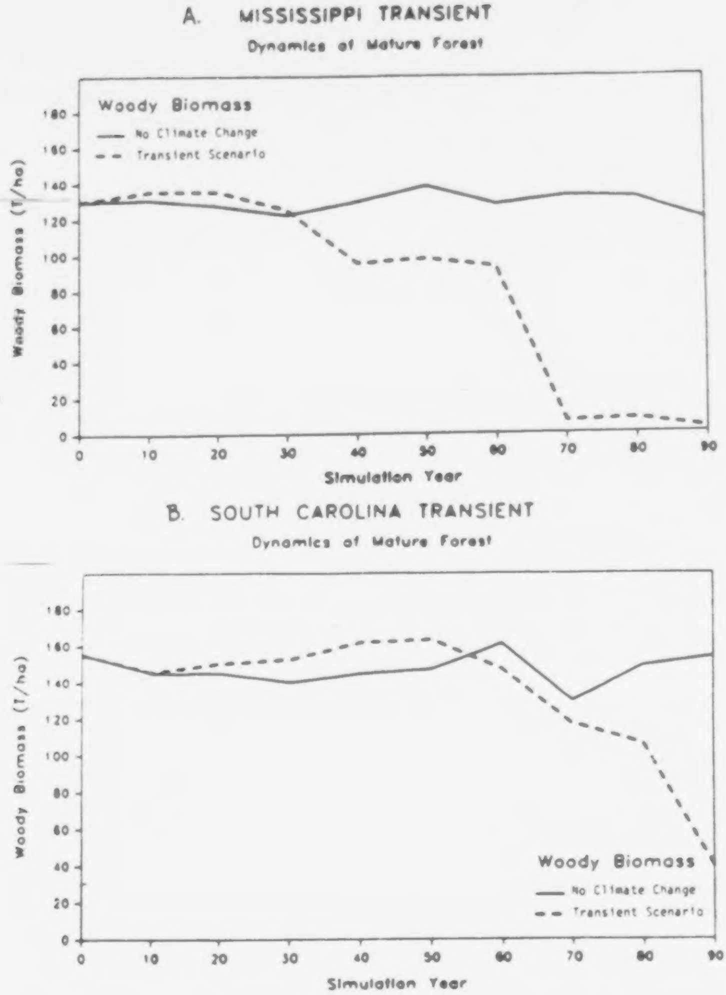


Figure 1-5. Projected changes in biomass (T/ha=2.24 t/acre) of mature forests in Mississippi (A) and South Carolina (B) under the GISS transient climatic change scenario (Chapter __; Urban and Shugart, Volume _), shifts toward drier conditions and the prairie advances to the East. Presumably changes in western forests would result from similar mechanisms. The drought-induced declines in forests might be partly offset if CO_2-induced increases in water-use efficiency were realized.

primarily affect sensitive life history stages but can also affect adult trees.

All of the study approaches used under all of the climatic scenarios predict major forest declines in the southern parts of species ranges and expansions to the north. These declines, resulting primarily from drought stress, would occur despite the differing rainfall predictions. Increases of temperature would severely reduce water intake, and therefore, would produce drought. Although precipitation could increase slightly in some U.S. locations, generally the increased evaporative demand caused by higher temperature would be a greater factor. Subsequent differences in rainfall between the various climate scenarios would modify the magnitude of regional drought patterns. The western limits of eastern forests could similarly retract as the climate. Existing forests probably would not shift intact, but would change in composition. Variations in migration rates and sensitivities to weather variables produce individual responses to climate change. These changes are consistent with the well-known dynamic nature of ecosystems and were projected for the forests of all regions. In the Great Lakes region, for example, beech would decrease in abundance, and birch and maple would increase (Zabinski and Davis; Botkin et al.). On some lands, forest productivity could remain about the same as today, but changes to less economically important species could be significant.

Not considered quantitatively in any of the studies are changes in forest disturbance regimes. These changes should not be considered lightly. Extreme and more frequent climatic variations (see Chapter 17) could cause much higher mortality in U.S. forests than the current experience. Although little is known as yet, some locations may experience an increase in the frequency of extreme weather events, for example, wind, ice, or snow storms, droughts, and flooding. Besides the direct damage these events can cause, they can cause drainage from insects, disease, and wildfires.

Study Limitations

Although predicted effects vary, these six analytical studies have results that are collectively consistent enough to advance our knowledge and justify concern regarding the future of U.S. forests under rapid climate change. The range of predicted effects is large; however, uncertainties exist regarding (1) the climate scenarios; (2) the kind and rates of responses of individual tree species; and (3) changes in forested ecosystems as a whole from environmental change. All of these factors significantly influence the precision and accuracy of the results.

A major uncertainty in the simulation model approach involves the rates of species dispersal into a region. The current generation of models has no dispersal mechanisms. A species is simply present or it is not present. For example, Botkin et al. excluded more southern tree species so that their dispersal was unrealistically nonexistent, and these southern species could never enter the region. But if they had been included in the simulations, these species would have entered the northern forests at the same rate as the climate change. This would have assumed dispersal rates far in excess of reality. This limitation can, in part, be overcome by studies, such as those of Zabinski and Davis, that provide some insight into actual dispersal rates and species migration.

The models also carry assumptions about the environmental controls of species limits. In most cases these assumptions are reasonable, given that the assumed control (for example, July temperature or annual rainfall) is usually related to the actual control, perhaps accumulated warmth or summer drought. However, large uncertainties exist in some instances. This is particularly true with regard to the climatic controls of the southern limits of southeastern forests, simply because of their association with the continental margin. Does the climate at that latitude represent the actual climatic limitation to the distributions, or are the species simply stopped by a geographic barrier? No one really knows. These uncertainties were partially addressed by Overpeck and Bartlein, who compared their fossil pollen approach to the modeling approach. The two approaches use similar relations to climate. Both approaches can be used to simulate forest distribution in the geologic past and both do reasonably well.

Several uncertainties with the pollen-climate correlation approach limit its precision and accuracy. First, many of the plant taxa used in the study are plant genera (e.g., pine, oak) rather than species, and thus the simulated results are not taxonomically precise. Second, the results are applicable only on a regional scale; local scale predictions are not made. Third, and very significant, the simulated results assume that all the plants are in equilibrium with the new climate. Rates of dispersal vary between species, and several hundred years may pass before plant communities are again in equilibrium with climate. How this lag would affect vegetation dynamics is not addressed in this study and is an important research question.

The paleoecological analysis of the past vegetation in the Sierra Nevadas (Davis) presents several uncertainties. First, differences with respect to weather variations (i.e., season to season and year to year) could produce strikingly different types of vegetation. Also, there is a large uncertainty about what the most appropriate analog period might be -- or if one even exists! Furthermore, the rate of climatic change in the future is predicted to be much faster than the rate of climatic change during the past 20,000 years. Lags in the response of species to the future climate could strongly affect the type of forest at any one location, whereas in the past, with a more slowly varying climate, lags in species response were not as important in determining forest composition. To the extent that climatic regimes predicted for the future are similar to the climates of certain periods in the past, a picture of future forests can be estimated from these past periods.

All of the studies are deficient in some very important processes controlling forest responses to climate, particularly disturbance regimes such as fires, windstorms, hurricanes, landslides, and pest outbreaks. In addition, the responses of mature trees to elevated CO_2 under conditions of moisture, temperature, or other nutrient limitations remain largely unexplored. Most research on elevated CO_2 on plants has been performed in controlled chambers using seedlings (Strain and Cure, 1985). However, the seedlings were not previously grown in or acclimatized to high CO_2 environments. Evidence has shown that plants grown under high CO_2 will respond much differently to changes in temperature, light, and moisture conditions (Strain and Cure, 1985). However, our ability to extrapolate CO_2 fertilization results from laboratory experiments to the natural world is limited, and our understanding of regional changes in water use efficiency is even less. Furthermore, complex interactions between fertilization effects and changes in water use efficiency can produce unexpected problems such as reduced heat tolerances due to effects on evaporation cooling. These interactions are least understood, but could produce major regional changes in forest responses. Therefore, it is not yet possible to quantitatively incorporate the direct effects of CO_2 on forests into studies such as these. Further, if water or nutrients are limiting to forest growth, then the effects of carbon fertilization may not be significant.

NATIONAL, ECOLOGICAL, AND SOCIOECONOMIC IMPLICATIONS

The effects of the predicted climate changes resulting from a doubling of CO_2 by 2030 may be considered from two perspectives: ecological and socioeconomic. Evidence for significant national implications is strong from both viewpoints.

Ecological Implications

Ecological implications for forests commonly start with tree response. But strong implications also exist in regard to other ecosystem components, e.g., animals, soils, water, secondary impacts, and as noted, the atmosphere through which climate change is mediated. Forest effects are described in terms of tree distribution changes and biomass production changes, but among the other major components, there is a host of interacting processes. Thus, significant changes in tree response would be accompanied by ecological reverberations throughout all the forested areas of these regions.

Tree distributions and biomass productivity

Forest migrations to the north in response to rapid warming in North America during the next century will be likely. However, significant lag is possible. Even under the maximum rates of species dispersal estimated by Zabinski and Davis, healthy forest areas may not redevelop for several centuries. Meanwhile, forest decline would not be under such constraints, so the extent of healthy forested regions in the United States probably would be greatly reduced. Though some locations may have increased productive potential from a biomass per hectare standpoint, the large reductions in areas with healthy forests would likely create a net reduction in forest productivity for the United States for several centuries.

Even if a massive reforestation effort were undertaken, the new forests resulting from species shifts may or may not be as productive as existing forests. More northern latitudes or higher elevations raise other considerations. Farther north, days are longer in the summer and shorter in the winter. At higher elevations, damaging ultraviolet light intensity is greater. All of these conditions could lower forest productivity below optimum and could hinder reproduction and survival.

Animals

A change in the size and relative homogeneity of forests could influence whether some animals can continue to live in habitats to which they have adapted.

Depending upon the species, animal migration can be hindered by boundaries between forests and other land types or facilitated as animals move along edges. In turn, some animals prefer young forests, and others prefer old forests. Some animals can exert a profound influence on forest structure and composition through selective browsing of seedlings, insect attack of different tree species, and other effects. All of these factors combine to influence the regional patterns of biotic diversity of both plants and animals (see Chapter___).

Soils

Soils under warmer climates also would change, though at a much slower rate than shifts in species distribution. Optimum soil conditions for high forest productivity supporting species at more northern latitudes or higher elevations might take several centuries to develop. Furthermore, it is not at all clear that some northern soils could even support more southerly species. The soils of the boreal forest are vastly different from those under the deciduous forests to the south.

Water

Where forests give way to drier conditions (e.g., in the Great Lakes and California), many lands now serving as watersheds might be used for a different purpose. Furthermore, regional-scale disturbances (such as fire) and applications of chemicals (such as fire retardants, fertilizers, and pesticides) could degrade regional water quality and increase airborne toxic chemicals (see chapter on Water Resources in this report).

Sea level rise is an additional water impact related to some forests. Projections for sea level changes are up to 1 meter (3 feet) in the next century (see Sea Level Rise chapter in this report). Many forest lands of high value for timber production (e.g., in the Southeast) or recreation (in the Northeast, Northwest, and California) are close to ocean coasts. Inundations, decreases in depth to the water tables, and saltwater intrusions could trigger rapid forest declines near these areas.

Secondary Impacts

As the southern bounds of forests tend to shift north, forest decline (sick and dying trees) could become extreme over vast areas. These areas would be highly susceptible to weed competition, pest outbreaks, or wildfire. As forests decline, species of lower economic value such as chokecherry, as well as weedy shrubs and herbs, could invade via wind dispersion. Under stressful environments, such species are severe competitors to most commercial tree species.

Trees experiencing less favorable growth conditions are more stressed and will be vulnerable to insect and disease attack. These secondary pest impacts could last "until the most vulnerable forest stands or tree species are eliminated" (Hedden, 1987). In addition, the incidence of catastrophic wildfires is predicted to increase in U.S. forests with higher temperatures. Simand and Main (1987) estimated an 8% rise in the occurrence of fires and a 20% increase in fire-suppression costs.

Socioeconomic Implications

The United States enjoys substantial economic and cultural benefits from its forests. Until recently, the nation's forest managers assumed that these benefits could be sustained by maintaining forests in a healthy condition (Fosberg, 1988). This was achieved, for example, by preventing fires or pest invasions, avoiding careless use, and enhancing productivity through good silviculture.

Beginning with the possibility of damage from regional air pollution damage to forests, suspected in the 1980s, alterations of the environment external to forests presented a new concern. Research and policy discussions to deal with this issue are ongoing.

If climate changes as rapidly as predicted, this additional external influence with its more global dimensions looms as a possible hazard to forests and their use. As can be imagined, a list of potential socioeconomic concerns would be large. To provide a brief perspective, three issues are considered.

Quality of the Human Environment

The forest amenities enjoyed by most U.S. citizens will be affected according to different forest responses. In the Boston-Washington corridor, a composition change from predominantly hardwood to more pine forests, though ecologically significant, would probably only superficially affect most people. In the Atlanta-Southeast region, the southern pine forests, while undergoing a gradual expansion of their northern boundaries, would have less vigor in the remaining stands. This could raise their vulnerability to damage by insects and disease, reducing esthetic values -- at least an intermediate impact for most of the local citizens. In contrast, drier climates in the Great Lakes and California regions may cause the loss of some forest lands to prairie or desert conditions, respectively -- a severe change for the people there, not only in their living environment but also in the whole spectrum of forest land use.

Recreation

Forests must be in a relatively healthy condition to support quality recreational use (Clawson, 1975). Forests undergoing gradual composition changes might remain healthy, but rapid changes would most likely cause stressed or declining forests. Such forest conditions would have less recreational appeal because of such factors as less pleasing appearance, greater threat of wildfire, and reduced hunting quality when game populations change or are diminished. Furthermore, drier conditions in U.S. forests would harm recreational opportunities that depend on abundant water or snow.

Wood Products

Altered U.S. forest productivity resulting from climatic change would have obvious major economic impacts. Significant yield reductions could lead to unemployment, community instability, industrial dislocation, and increased net imports of wood products.

Reforestation projects could make up for some losses in forest productivity and artificially advance migrations forced by climatic change. Reforestation technology has greatly improved in recent decades so that success rates also have increased greatly. Examples are high-vigor seedlings through improved nursery practices, genetic selection, and tissue culture. Improvements in the field include machine planting, fertilization, and weed control on selected sites. Results are evident from the large acreages of plantations established in the United States in recent decades, particularly with loblolly pine in the southeast and Douglas-fir in the Pacific Northwest (see Table 11-5).

Innovative manufacturing trends should prove to be timely during times of rapid forest change. High-strength and durable products from reconstituted wood (e.g., new particle board concepts, warp-proof hardwood lumber, paper products of fiber from multispecies) are now in use or well along in development. These new methods will lessen the present overdependency on a few commercial conifer species from stands above minimum size and quantity (Ince, 1987). The result will be an ability to use the timber resources of the future, however they change in composition.

Table 11-5. Levels of management within U.S. forests in 1977 as illustrated by areas in three broad uses within four major regions. Intensively managed are represented by plantations[2]; moderately managed are those forests naturally established but with commercial rates of growth[3]; and forests with protection as the primary level of management (i.e. deferred or reserved[4]; estimated from tables 3.1 and 9.2, USDA, 1982).

U.S. Regions	Management level (millions of hectares[1])			
	Intensive	Moderate	Protected	Total
East				
North	3	65	4	72
South	8	69	7	84
West				
Rocky Mountain	1	23	32	56
West Coast (WA, OR, CA)	3	22	13	38

---

1. Ha x 2.47 = acres

2. Plantations are forests established by seeding or planting, generally on the most productive lands, and followed by silvicultural tending such as thinning, fertilization and weed control until harvest at an economically optimum age.

3 and 4. Definitions in Table 11-1.

NATIONAL FOREST POLICY AND CLIMATIC CHANGE

Historically, U.S. forest policies have undergone continued development to meet national change (Young, 1982). The earliest policies were adapted by the New England colonies in the 1600s to regulate overculturing near settlements. Wood was needed for fuel and buildings, but existing methods were not capable of long distance log transportation. Development of U.S. forest policies continued and has been particularly intense this century, as the National forests, National parks, and wilderness areas were established.

At present, forest managers are dealing with many additional policy issues. Five of these (Clawson, 1975) are important to climatic change/forest response:

- How much U.S. land should be devoted to forests?
- How much forest land should be withdrawn from timber production and harvest?
- How should the Federal forest lands be managed? (That is, the lands under the USDA Forest Service, USDI Park Service, Bureaus of Land Management and Indian Affairs, etc.)
- What constraints (e.g., mandatory forest practices) should be placed on forest managers to ensure national environmental goals?
- Who should pay the additional costs incurred in implementing new policies?

The large array of forest ownerships in the United States makes development and implementation of forest policy more complicated than in most countries, where nearly all forests belong to the government. The diversity of owners and managers results in widely divergent goals and objectives.

How Much Land Should Be Forested?

Changes in forest composition or regional boundaries induced by rapid climatic change would magnify the complexity of National forest policy even further. Lands in forests now would require review relative to such competing needs as agriculture and residential use (which would also be adjusting to climatic change).

How Much Should Be Withdrawn From Timber Production?

Where the productivity of wood is significantly reduced, increased, or shifted, a policy question that would surely arise concerns whether forest lands should be reallocated to maintain timber production. If so, how should competing forest uses, such as watersheds, parks, and wilderness, be treated? How much of each can the United States afford under changed climatic conditions? Should the Federal Government purchase more forest lands to support all public needs?

In the short term, forest managers could compensate for some loss of productivity by improved technology, though at increased costs. An example would be establishing more drought-tolerant plantations through genetic selections, improved nursery stock, and more intensive silvicultural practices (e.g., weed control and thinning). Introducing new species adapted to warmer climates might be possible in some locations, but this would call for developing new silvicultural regimes and use methods -- possible, but expensive in time and money. In the long term, if growing conditions become extremely difficult on some U.S. forest lands because of climatic changes, investment in tree crops at such locations could become unattractive altogether.

How Should We Manage Federal Forests?

The National forests under the USDA Forest Service are managed according to a series of complex legal directives and administrative procedures, beginning with the Organic Act of 1897 (Woodman). Ultimately, the objective became to manage the National forests for multiple uses, with timber on a sustained-yield basis and certain lands set aside as wilderness areas. The National Forest Management Act of the mid-1970s requires 15-year management plans for each National forest subject to public review.

Lands managed by the Department of Interior are under similar mandates. For example, a congressional act passed in 1976 charged the Bureau of Land Management to manage its 2.3 million ha of forest and range land according to multiple-use and sustained-yield principles. Similarly, the National Park Service is mandated to manage National parks, monuments, historic sites, and so forth, for the recreational enjoyment of people. Such activities as timber harvesting, hunting, mining, and grazing are not permitted. In addition to the Federal Government, most States, many counties, and some municipalities own forest lands.

The Forest and Rangeland Renewable Resources Planning Act of 1974 requires the Secretary of Agriculture to make periodic reviews of the nation's forest and rangeland resources. The act was amended in 1976 to also require management plans for the National forests. In the future, these assessments and planning efforts should include consideration of the possible effects of predicted climatic changes. One key issue is the level of priority given to maintaining forest health under changed climatic conditions. For instance, under more adverse environments, should National forests be left to decline as a natural process, thereby losing esthetic values in parks, water yields from watersheds, and highly productive timber crops? Or should silvicultural forest techniques, such as thinning, weed control, and fertilization, be employed to "save" them? This question and others will challenge the fundamental concepts of the benefits of multiple use and sustained yield of forests.

How Can We Ensure National Goals?

At the minimum, Federal agencies must plan and act in concert with the State forest organizations. In the first half of this century, the Federal Government attempted to regulate forest harvests on Federal and private lands. Development of this policy did not survive strong public concern and intense political debate against such policy (Worrell, 1970); the same sentiment would likely exist today and in the near term. However, under the influence of rapid climatic change, the nation may once again have to face the touchy issue of what restraints or forest practices must be regulated for all public and private lands.

Solomon and West (1985) point out that while climatic change might disrupt forest ecosystems in the future, it is uncertain whether forest managers could or would be able to apply silvicultural practices on a scale large enough to maintain the net productivity of commercial forest lands in the United States. Some States (e.g., Washington, Oregon, and California) have laws specifying fire protection requirements, control burn practices, and reforestation minimums following timber harvests. Zoning, permits, licenses, and various taxation measures also have been attempted with mixed results. It is much easier to prevent owners from destroying forests than to compel them to implement silvicultural practices.

To keep pace with the rapid climatic changes projected, the U.S. reforestation effort conceivably would need to be doubled or tripled in size. In recent years, about 800,000 ha (2 million acres)/year (approximately 700+ million seedlings) have been reforested in the United States (USDA, 1982). Costs range from $200 to $700 per ha ($80 to $280 per acre) depending upon species, site preparation, plantation density, and planting method. Using $500 per ha ($200 per acre) as a mode, the total annual expenditure is near $400 million. About 0.4% of the commercial land base is reforested annually. At this rate, it would take 100 years to reforest 40% of the U.S. forest lands, assuming no repeat hectares to cover failures or harvests of the first plantations.

An expansion on the scale suggested above would require large investments in seed procurement, tissue culture capability, nursery capacity, and research to improve knowledge about the establishment and silviculture of drought-resistant plantations. Even if the dollar commitments were made, reforestation at this scale might only be possible if all forest lands were managed by one organization. The complex forest ownership pattern in the United States, therefore, would be an issue to overcome in a national reforestation program.

Who Should Pay?

Adjusting forest policies to address the issues arising from climatic change will most likely raise the costs of using the nation's forests -- whether for water, recreation, aesthetics, or timber. Additional research to answer many new questions will also require more funds. A major question will concern who should pay for these costs. Land owners? Forest users? Consumers? All taxpayers? The answers will come when better information is available on resulting forest effects, followed by public debate establishing new priorities for forest use in a changed climate.

RESEARCH NEEDS

The forest effects resulting from rapid climatic change are at present hypothetical. The change has not yet occurred, and many uncertainties are associated with the predictions. Effective policies to deal with new forest effects will require more information and fewer uncertainties that must come through forest ecosystem research. Four broad questions concerning U.S. forests frame the research needs for the 1990s: What will the effects be? How can they be measured reliably? How should they be managed? How can we ensure that research will be conducted in a timely fashion?

Effects

What will be the effect on the nation's forest ecosystems if climatic changes occur as predicted by the middle of the 21st century? While subsets of this question must include extent, magnitude, and risk considerations, additional knowledge is needed concerning the following factors:

1. Forest migration processes and rates, including the landscape processes that control the horizontal movements of forest, animals, and disturbances;
2. Interactions among the different landscape components and land-use practices that affect biodiversity, and water quantity and quality;
3. The impact of climate change alone and in combination with other natural or anthropogenic influences, such as insects, pathogens, CO_2 enhancement, air pollutants, UV-B radiation, and acid deposition on U.S. forests; and
4. The processes and mechanisms that play key roles in forest ecosystem effects -- both biologically as in photosynthesis and respiration, and physically as in flows of energy, carbon, water, and nutrients through ecosystems.

Methods

How can forest ecosystems be measured to reliably detect the effects of rapid climate change? Today, the response of ecosystems to environmental change is largely based upon extrapolating from field observations, from knowledge about seedlings or individual trees of a small number of commercially valuable species, and from computer models. The following must be accomplished:

1. A determination of the most useful integrating variables for forest ecosystems that indicate the effects of climatic change;
2. Effective sampling designs developed for experiments and long-term monitoring at the forest ecosystem scale; and
3. Improved models capable of projecting regional effects on forests across multiple spatial and temporal scales.

Management

What options are available to the public and private forest managers and owners in the United States to deal with the changes in the nation's forests that might occur in the next century? Research is needed to accomplish the following:

1. Understand the socioeconomic impacts of all forest ecosystem effects to clarify economic risks and alternatives; and
2. Develop technology to mitigate the adverse effects or to exploit the benefits of forest change, such as breeding, bioengineering, transplanting, fertilization, irrigation, and other management approaches.

Timing

The timing of the research is critical. The effects of climatic change may be some decades away, but this should not lessen the urgency to begin research toward better information and methods. The complexities of the science are very large. To build the required base of knowledge to deal with potential forest changes before they are upon the nation will require significant time and resources.

REFERENCES

Barbour, M.G., J.H. Burk, and W.D. Pitts. 1987. Terrestrial Plant Ecology, 2nd ed. Menlo Park, CA: Benjamin/Cummings Publishers.

Botkin, D.B. 1979. A grandfather clock down the staircase: stability and disturbance in natural ecosystems. In: Waring, R.H., ed. Proceedings of the 40th Annual Biological Colloquium. Forests: Fresh Perspectives From Ecosystem Analysis. Corvallis, OR: Oregon State University Press, pp. 1-10.

Clawson, M. 1975. Forests for Whom and for What? Resources for the Future. Baltimore, MD: Johns Hopkins University Press.

Cubbage, F.W., D.G. Hodges, and J.L. Regens. 1987. Economic implications of climate change impacts on forestry in the South. In: Meo, M., ed. Proceedings of the Symposium on-Climate Change in the Southern U.S.: Future Impacts and Present Policy Issues. New Orleans, LA: U.S. Environmental Protection Agency.

Fosberg, M.A. 1988. Forest productivity and health in a changing atmospheric environment. In: Berger, A., ed. NATO Symposium on Climate and Geosciences. Dordrecht, The Netherlands: Reidel Publishing Company. In press.

Hammond, A.L. 1972. Ecosystem analysis: biome approach to environmental science. Science 175:46-48.

Hedden, R. 1987. Impact of climate change on forest insect pests in the southern U.S. In: Meo, M., ed. Proceedings of the Symposium on Climate Change in the Southern U.S.: Future Impacts and Present Policy Issues. New Orleans, LA: U.S. Environmental Protection Agency.

Ince, P.J. 1987. Technology, timber demand and timberland investment. In: A Clear Look at Timberland Investment, Milwaukee, WI, April 27-29, 1987. Conference proceedings. Forest Products Research Society.

Lavdas, L.G. 1987. The impact of climate change on forest productivity. In: Meo, M., ed. Proceedings of the Symposium on Climate Change in the Southern U.S.: Future Impacts and Present Policy Issues. New Orleans, LA: U.S. Environmental Protection Agency.

Leverenz, J.W., and D.J. Lev. 1987. Effects of carbon dioxide-induced climate changes on the natural ranges of six major commercial tree species in the western United States. In: Shands, W.E., and J.S. Hoffman, eds. The Greenhouse Effect, Climate Change, and U.S. Forests. Washington, DC: Conservation Foundation, pp. 123-156.

Manion, P.D. 1981. Tree Disease Concepts. New Jersey: Prentice Hall.

Meo, M., ed. 1987. Proceedings of the Symposium on Climate Change in the Southern United States: Future Impacts and Present Policy Issues. May 28-29, 1987. New Orleans, LA: University of Oklahoma and U.S. Environmental Protection Agency.

Miller, F.W., P.M. Dougherty, and G.L. Switzer. 1987. Effect of rising carbon dioxide and potential climate change on loblolly pine distribution, growth, survival and productivity. In: Shands, W.E., and J.S. Hoffman, eds. The Greenhouse Effect, Climate Change, and U.S. Forests. Washington, DC: Conservation Foundation, pp. 157-188.

Pickett, S.T.A., and P.S. White. 1985. The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, Inc. Harcourt Brace Jovanovich.

Schallau, C.H. 1988. The forest products industry and community stability: the evolution of the issue. Montana Business Quarterly Summer: 1-8.

Shands, W.E., and J.S. Hoffman. 1987. The Greenhouse Effect, Climate Change, and U.S. Forests. Washington DC: Conservation Foundation.

Simand, A.J. and W.A. Main. 1987. Global climate change: the potential for changes in wildland fire activity in the Southeast. In: Meo, M., ed. Proceedings of the Symposium on Climate Change in the Southern U.S.: Future Impacts and Present Policy Issues. New Orleans, LA: U.S. Environmental Protection Agency.

Solomon, A.M., and D.C. West. 1985. Potential responses of forests to CO_2 induced climate change. In: White, M.R., ed. Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health. Washington, DC: U.S. Department of Energy. DOE/ER-0236. pp. 145-1709.

Chapter 11

Solomon, A.M., and D.C. West. 1986. Atmospheric carbon dioxide change: agent of future forest growth or decline? In: Titus J.G., ed. Effects of Changes in Stratospheric Ozone and Global Climate, Vol. 3: Climate Change. Washington, DC: U.S. Environmental Protection Agency.

Spurr, S.H., and B.V. Barnes. 1980. Forest Ecology, 3rd Ed. New York: J. Wiley & Sons.

Strain, B.R., and J.D. Cure, eds. 1985. Direct Effect of Increasing Carbon Dioxide on Vegetation. Washington, DC: U.S. Department of Energy. DOE/ER-0238.

Tirpak, D.A., ed. 1987. Potential Effects of Future Climate Changes on Forest and Vegetation, Agriculture, Water Resources and Human Health, Vol. V. Assessing the Risks of Trace Gases That Can Modify the Stratosphere. Washington, DC: U.S. Environmental Protection Agency. EPA 400/1 - 87/001E.

Titus, J.G., ed. 1986. Climate Change, Vol. 3. Effects of Changes in Stratospheric Ozone and Global Climate. Washington, DC: U.N. Environmental Program and U.S. Environmental Protection Agency.

USDA. 1981. U.S. Department of Agriculture, Forest Service. An Assessment of the Forest and Range Land Situation in the U.S. Forest Resource Report No. 22.

USDA. 1982. U.S. Department of Agriculture, Forest Service. An Analysis of the Timber Situation in the U.S. 1952-2030. Forest Resource Report No. 23.

White, M.R., ed. 1985. Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health. Washington, DC: U.S. Department of Energy. DOE/ER-0236.

Worrell, A.C. 1970. Principles of Forest Policy. New York: McGraw-Hill.

Young, R.A., ed. 1982. Introduction to Forest Science. New York: J. Wiley & Sons.

RISING CARBON DIOXIDE, CLIMATE CHANGE, AND FOREST MANAGEMENT: AN OVERVIEW

by Robin Sandenburgh, Carol Taylor, and John S. Hoffman[1]

ABSTRACT

Rising carbon dioxide (CO_2) will alter the biochemical processes of trees and plants, changing growth rates and productivity. Moreover, environmental change resulting from increased atmospheric CO_2 could alter the potential productivity of the world's forest regions. Changes are likely to affect timber-growing regions of the United States in different ways, particularly intensifying extremes in temperature, rainfall, and wind. Changes in the environment over the life of a stand could exceed those of the past century; trees being planted today could experience the most productive parts of their lives in conditions quite different from today's.

An accumulation of atmospheric CO_2 could directly alter biochemical cycles in ways which influence the distribution of species and forest productivity. These include change in the rate of photosynthesis, change in water-use efficiency, and increased nitrogen fixation. In addition to biochemical changes, there is likely to be increased risk of loss to fire and pests.

To maintain or enhance forest productivity, adjustments will be required in forest technology, resource allocation, planning, and decision making.

If scientific theories about the effects of rising levels of carbon dioxide (CO_2) prove correct, the planet's average temperature will increase significantly over the next century, changing regional climatic conditions (National Academy of Sciences, 1979). Rising atmospheric CO_2 will alter biochemical processes of trees and plants, changing both growth rates and productivity (Wittwer,

---

[1] This material is adapted from the report *Strategic Options for Enhancing Forest Industry Productivity in the Face of Rising Atmospheric Carbon Dioxide*, prepared by ICF Incorporated for the U.S. Environmental Protection Agency.

1978). Together these changes will disrupt ecosystems and change growing conditions of forested regions throughout the world, with decade-to-decade changes occurring faster than at any time in the history of managed forests and with cumulative changes over several decades vastly exceeding those of the past. These environmental changes could alter the potential productivity of the world's forest regions. Actual forest productivity will depend, however, not just on these environmental changes but on the responses of forest managers.

If the National Academy of Sciences' panel on CO_2 is correct, cumulative changes in the environment over the life of various tree species will exceed those of the past century. Trees being planted today will experience the most productive part of their life cycles in conditions quite different from today's.

Changes in local climate associated with global warming could include shifts in:

- average precipitation, evaporation, and soil moisture;
- the frequency of extremes such as the likelihood of droughts or floods;
- the total variability of climatic conditions faced over the life of a stand;
- seasonal characteristics, such as first or last frost or summer dryness; and
- frequency of damaging storms (Manabe et al., 1981).

The changes will not be the same everywhere: the climate in some regions could become warmer and wetter and in others, warmer and drier. The temperature will increase more in higher latitudes, less in equatorial areas.

In addition to climate effects, rising atmospheric CO_2 amounts may also increase plant growth by affecting photosynthetic rate and plant physiology. Higher levels of CO_2 may lower plant water requirements and allow soil microbes to "fix" greater amounts of nitrogen (Hardy and Havelka, 1975). Specific effects will vary among tree species as well as among varieties and populations within a species. These effects will also depend, in part, on changes in climate. At present, the extent of biochemical and physiological changes in different species and under different environmental, climatic, and management conditions is far from clear. The evidence, however, indicates that productivity will be higher than without the CO_2 fertilizer effect and that forest companies can enhance possible increases by selecting the most responsive species and by appropriately managing other resource inputs. Whether or not the combined effects of climate change and CO_2 fertilization will be positive or negative is unclear; it is certain, however, that prior planning can reduce losses or enhance increases as the environment changes.

Planning for Climatic and Biochemical Change

The combined effects of climatic and biochemical change could influence the potential productivity of key silvicultural regions. The productivity of a given forest region will be determined by how particular species grow over an entire life cycle. This, in turn, is a function of natural growing conditions over time, technologies and resources available, and decisions to apply these management options over the long haul. If CO_2 induces changes in natural growing conditions, adjustments will be needed in forest technology, resource allocation, planning, and decision making to maintain or increase productivity.

Many factors combine and interact to determine growth, so projection of ultimate effects is difficult. Because CO_2 and other greenhouse gases have not accumulated nearly as much in this century as they will in the next, direct experience is insufficient to evaluate what will happen. Using evidence from past changes in climatic conditions nevertheless offers one method of generating hypotheses about how CO_2-induced change could influence growing conditions and overall productivity. A second method is to look at how productivity varies with different growing conditions found in existing climate regions. Neither analogue method, however, accounts for the dynamic dysequilibrium that CO_2 could induce. No region existing today has experienced changes in year-to-year and decade-to-decade conditions equal in magnitude to those that could occur under rising CO_2 nor have any regions simultaneously experienced equivalent changes in biochemical and physiological processes.

Regional Climatic Change

Because researchers studying CO_2 buildup agree that regional climates will change more than global averages, the concentration of important forests in certain regions is important. In the United States, three regions, the South, North, and Pacific, account for 95% of the nation's annual timber production (U.S. Department of Commerce, 1976). Worldwide timber holdings also are concentrated regionally. It is unlikely, however, that all regions would either improve or worsen; it is equally unlikely that each, or any, would be influenced in the same way.

Distinct natural distribution patterns for most species of trees are the clearest evidence that tree growth depends on climate. Cypress trees do not flourish in Minnesota, Douglas-fir is not apt to be highly productive in Florida, and no trees grow in the Sahara Desert or on Antarctica.

Silvicultural management decisions recognize the importance of local weather and climate parameters to plant growth and output. Managers choose tree species and varieties for the climate of an area, including expected climate variations over a stand's lifetime. Yet, if climatic norms and expected variances are so important to tree growth, what will happen as these norms and variances shift continually and in one, warm, direction? Layser (1980) reviewed historical studies on the influence of regional climate on forest productivity and concluded that:

> ... it would appear that climate change may significantly affect projected yields and rotation length for forest tree species, and might have a bearing on the concept of sustained high-yield forestry....Since trees keep their genetic make-up throughout a long life...forest managers may need to take climatic trends into account in silviculture, and view site as a dynamic, not static, concept.

The principles of silviculture suggest that changes in weather extremes could be important to forest growth. CO_2-induced climate change could alter current extreme weather conditions either way, producing greater or fewer stressful periods. Of the fundamental climate factors--wind, temperature, and rainfall--rainfall is the single strongest influence on growth.

Temperature Extremes

Although higher levels of atmospheric CO_2 are expected to have a warming effect overall, average temperatures will vary regionally, and extreme temperature conditions could increase or decrease in some regions. For example, if an area experiences more "cold snaps," higher tree mortality rates may result. The surviving trees may suffer loss of vigor and show subsequent decreases in budding. As a result, the natural regenerative capacity of the forest would be reduced. Conversely, fewer cold snaps in northern areas would reduce such problems there.

In some areas, trees exposed to more heat waves could suffer short-term water stress, diminished vigor, and enhanced vulnerability to external attacks by insects and disease. Conversely, an area now subject to heat waves might have fewer because of changing circulation patterns, decreasing this stress.

Precipitation Extremes

Most forest species are resilient enough to withstand occasional drenching rains, extreme dry periods, and even short-term inundation without experiencing significant losses. Numerous precipitation extremes--in either direction--will reduce productivity of the species being planted now, however. More frequent wet conditions over time could increase insect and pest populations and, by increasing soil moisture, enhance potential root damage. Too frequent dry conditions in a given period, on the other hand, could lead to water stress. Again, the converse holds: less-productive regions may be favored by changes in drought or flood occurrences.

Wind Extremes

Particularly in the critical first stage of forest establishment, extreme winds may be crucial. Seedlings grown on level, windswept, open-field sites have shown less vigorous growth, reduced leaf area, and greater foliage damage than those grown under similar soil conditions but in forest openings or protected fields (Spurr and Barnes, 1973).

From a management viewpoint, wind is a force because it is potentially destructive. Few forests can stand the devastating wind velocities of a hurricane or tornado, but some species are better suited than others. An area never hit by hurricanes likely is planted with a species ill-suited to gale winds. Beyond the destruction from major windstorms, however, is breakage attributed to lesser, "normal" winds. Fewer windstorms of course would improve the potential productivity of an area and open it to new species.

Forest Fire Risk

In regions where average temperature increases and average rainfall drops, the risk of fire goes up. In the last decade, annual fire losses in National Forests and adjacent areas alone amounted to more than $100 million (U.S. Forest Service, 1980). If summers become drier, the work of Manabe et al. suggests that fire becomes a powerful threat (Manabe et al., 1981).

Even though advances in forest fire management since the early part of the century are impressive, small changes in climate can overshadow any progress. In the last decade, the incidence of fires went up (Nelson, 1979). Data on the relationship of climate to fires in Canada and the United States show the weight of climate (U.S. Department of Agriculture, 1981). The 4.8 million-hectare area that burned in 1980 was 28% greater than the area burned in 1961, the previous record year, prompting the Canadian government to report that:

> Preliminary data support the idea that an upward trend in burned area is linked both to the increased use of the land by people, and to worsening climatic trends during the past two to three decades (U.S. Department of Agriculture, 1981, emphasis added).

Losses to Pests

Millions of dollars are spent annually by forest managers to control insects, weeds, bacteria, fungi, and predators. Despite improved pest control, current losses average about 25% of total output (Pimental *in* U.S. Department of Energy, 1980).

Fungi and insects are especially dependent on temperature. The well-being of pathogens, fungi, bacteria, and weeds is tied to water availability. Moreover, warmer temperatures could change the range and geographical region of insects during winter and, hence, the areas in which niches can be established for the next growing season. Weather patterns and pest outbreaks correlate. For example, the 1912 and 1949 spruce budworm outbreaks were statistically associated with dry, warm fall weather patterns (Haynes, 1984).

Whether pests increase or decrease, they will nevertheless be affected by climatic alternations. As one author put it:

> ... insects and plants are evolving, competing, interdependent systems. Because they have evolved together for eons, the balance between them may be very fine and easily, unwittingly, unrecognizably, and irrevocably altered by our actions (Stark, 1977).

CHANGES IN PLANT PHYSIOLOGY

Trees and other plants establish niches in an ecosystem and grow and compete on the basis of biochemical and physiological processes that determine their competitiveness with other organisms. Accumulated CO_2 can directly alter biochemical cycles and physiological processes. Both theoretical and empirical evidence suggests that rising CO_2 levels can increase plant photosynthesis rates differentially and alter other biochemical cycles in ways that may influence the productivity of trees and plants, as well as their competitive distribution in natural ecosystems.

Photosynthesis

Carbon dioxide is essential to photosynthesis, the process by which plants convert water, sunlight, and CO_2 into sugars. Scientists who study photosynthesis believe that plant growth depends, in part, on CO_2. Evidence suggests that current ambient levels fail to provide sufficient CO_2 to permit maximum growth (Baker et al., 1983). If this is so, a rise in the ambient CO_2 available to plants could increase the rate of photosynthesis and plant growth, as long as other factors--water, nutrients, solar radiation, or internal plant processes--do not limit growth (Lemon, 1977). In other words, the level of CO_2 now available in the atmosphere may be stunting growth. More CO_2 may help trees grow faster (see Kramer and Sionit, this volume, for a full discussion).

Species are likely to differ in their responses to greater CO_2 exposure, as do different parts of populations within the same species. Despite observed differences, however, few of the physiological or biochemical factors that account for such significant differences really are understood. A review of many studies suggests several factors critical to determining plant responses to higher CO_2:

- the dependence of the plant on nitrogen for growth;
- the indeterminateness or determinateness of a species;
- the rate at which a plant grows during critical phases in its development; and
- the plant's ability to survive the stresses of each life-cycle stage as a result of numerous environmental and climatic factors (Tinus, 1974; Leidig, 1976; Allen, 1979; Kramer, 1981).

Biochemical and Physiological Processes

Scientists have studied the influences of higher ambient CO_2 levels on plant growth and productivity. Higher CO_2 concentration appears to improve water-use efficiency by decreasing stomatal aperture. Other work showed that an increase in CO_2 concentration of 250 parts per million above current levels improved both water-use efficiency and yield in water-stressed wheat compared to similar plants grown under normal CO_2 concentrations (Gifford, 1979).

Similarly enhanced nitrogen fixation was demonstrated in experiments growing soybeans under higher CO_2 levels (Hardy and Havelka, 1975): a threefold increase in ambient concentration resulted in a fivefold increase in nitrogen fixation.

Other effects demonstrated in experimental studies include greater branching, elongation of stems, increase in root/shoot ratios, larger leaf area and, in some cases, thicker leaves, and a hastening of bud initiation and flowering (Hesketh and Hellmers, 1973). These effects have been observed in only a few selected species; thus it is incorrect to draw general conclusions from these results.

The key issue for commercial silviculture is the extent to which increased photosynthesis and changes in other biochemical and physiological processes translate into increased yield over a tree's life. Evidence from plants grown in greenhouses and under experimental conditions, in which other factors (water, soil, and nutrients) are not limiting, does suggest that higher CO_2 levels could increase plant yield significantly. Conclusions of how much, however, are far from definitive--especially considering particular species grown under actual field conditions.

REFERENCES

Allen, L. H. 1979. Potentials for carbon dioxide enrichment. *In* B. J. Barfield and J. F. Gerber (ed.), *Modification of the Aerial Environment of Crops*. American Society of Agricultural Engineers, St. Joseph, Mich.

Baker, D. N., et al. 1983. The impact of increased CO_2 on photosynthesis and agricultural productivity. Mississippi State University, Mississippi State.

Gifford, R. M. 1979. Growth and yield of CO_2-enriched wheat under water limited conditions. *Aust. J. Plant Physiol.* 6, 367-378.

Hardy, R. W. F., and U. D. Havelka. 1975. Nitrogen fixation research: a key to world food. *Science* 188, 633-643.

Haynes, D. L. 1984. Effects on agricultural plant pests. Department of Entomology, Michigan State University, East Lansing.

Hesketh, J. D., and H. Hellmers. 1973. Floral initiation in four plant species growing in CO_2-enriched air. *Environ. Control Biol.* 11, 51-53.

Kramer, P. J. 1981. Carbon dioxide concentration, photosynthesis, and dry matter production. *Bioscience* 31, 29-33.

Layser, E. F. 1980. Forestry and climatic change. *J. For.* November, 678-682.

Ledig, F. T. 1976. Physiological genetics, photosynthesis and growth models. *In* M. G. R. Cannell and F. T. Last (ed.), *Tree Physiology and Yield Improvement*. Academic Press, Inc., New York. p. 212-54.

Lemon, E. 1977. The land's response to more carbon dioxide. *In* N. R. Anderson and A. Malahoff (ed.), *The Fate of Fossil Fuel* CO_2 *in the Oceans*. Plenum Publishing Co., New York.

Manabe, S., R. T. Wetherald, and R. J. Stouffer. 1981. *Summer Dryness Due to an Increase of Atmospheric* CO_2 *Concentration*. National Oceanic and Atmospheric Administration, Fluid Dynamics Laboratory, Washington, D.C.

National Academy of Sciences National Research Council. 1979. *Carbon Dioxide and Climate: a Scientific Assessment*. Report by the Climate Research Board. National Academy of Sciences, Washington, D.C.

Nelson, T. C. 1979. Fire management policy in the national forests--a new era. *J. For.* November, 723-725.

Spurr, S. H., and B. V. Barnes. 1973. *Forestry Ecology*, 2nd ed. The Ronald Press Co., New York.

Stark, R. W. 1977. Integrated pest management in forest practice. *J. For.* May, 251-254.

Tinus, R. W. 1974. Impact of the CO_2 requirement on plant water use. *Agric. Meteorol.* 14, 99-112.

U.S. Department of Agriculture. 1981. More on Canada's 1980 forest fire season. *Forest Fire News*, July.

U.S. Department of Commerce, Bureau of the Census. 1976. *Census of Manufacturers, 1972. Volume II. Industry Statistics. Part I. SIC Major Groups 10-26*. U.S. Government Printing Office, Washington, D.C.

U.S. Department of Energy. 1980. *Workshop on Environmental and Societal Consequences of a Possible* CO_2*-Induced Climate Change*. Report CONF-7904143 UC-11, October, 1980. U.S. Department of Energy, Washington, D.C.

U.S. Forest Service. 1980. *Annual Fire Report: 1979*. U.S. Government Printing Office, Washington, D.C.

Wittwer, S. H. 1978. Carbon dioxide fertilization of crop plants. *In* U.S. Gupta (ed.), *Crop Physiology*. IBH Publishing Co., Oxford.

EFFECTS OF INCREASING CARBON DIOXIDE CONCENTRATION ON THE PHYSIOLOGY AND GROWTH OF FOREST TREES

by Paul J. Kramer and Nasser Sionit

ABSTRACT

Short-term experiments indicate that increasing the concentration of atmospheric carbon dioxide (CO_2) increases stem diameter, height, and dry weight of seedlings of several tree species. A high CO_2 concentration also increases branching, leaf area, and leaf thickness in some but not all species. Root-shoot ratio does not seem to be significantly affected. At the end of the first growing season, dry weights of roots, stems, and leaves of sweetgum and loblolly pine seedlings were greater at 500 than at 350 parts per million (ppm) of CO_2. Sweetgum also produced more branches and leaves at the higher concentration. There was no significant increase in dry weight of roots, stems, or leaves at 650 ppm over the value at 500 ppm, but there was a significant increase in height of loblolly pine seedlings. It seems probable that if other environmental factors are not severely limiting, the increasing concentration of atmospheric CO_2 will significantly increase tree growth, but the magnitude of the effects will vary among species and with the severity of other environmental stresses. Although increasing concentration of CO_2 may partly compensate for low light, high temperature, and water stress and possibly even for mineral deficiencies, unfavorable factors such as droughts, abnormal temperatures, and unfavorable soil conditions will continue to limit tree growth. There is need for more long-term research to provide reliable information concerning the effects of CO_2 buildup on the relative growth of commercially important species.

Foresters have learned from experience how to cope reasonably well with environmental stresses, such as drought, waterlogged soil, mineral deficiencies, and unfavorable temperatures, by choosing appropriate species and management practices. Now a new environmental factor, the increasing concentration of atmospheric carbon dioxide (CO_2), has been identified. It is present worldwide and is inexorably increasing in importance. Unfortunately, the CO_2 problem has been identified only recently, and it is too new to have been evaluated fully. There is a tendency to postpone consideration of its effects until the future, when the concentration will have doubled, but trees are being affected now. The CO_2 concentration has increased about 15% during the past 50 years and probably will rise more rapidly during the next 50 years. The effects of this increase may already have been detected in the annual rings of subalpine conifers (LaMarche et al., 1984).

Presumably the major question for foresters is whether the changes in relative growth rates and wood production among the important commercial species will be sufficiently important to justify changes in choice of species for future planting. They need to know whether the tree species most successful today will be those most successful 50 or 100 years from now when the CO_2 concentration may exceed 500 parts per million (ppm). Various secondary questions concern effects on drought tolerance, mineral nutrient requirements, wood quality, branching, and damage from pests, all of which might affect management plans.

KNOWN EFFECTS OF HIGH CO_2 CONCENTRATION ON GROWTH

Greenhouse crops such as lettuce and tomatoes have been "fertilized" successfully with CO_2 for many years, and much research has been done on herbaceous plants. The early work was summarized by Miller (1938). Kimball (1983) surveyed the recent literature and collected 70 reports and over 340 observations on the effects of enhanced CO_2 on 24 agricultural crops and 14 other species. Evaluation of these data led him to conclude that the marketable yield of these herbaceous plants would be increased an average of 33% by doubling the CO_2 concentration of the atmosphere. However, this estimate seems to assume favorable environmental conditions. In contrast, Waggoner (1984) expects very small net effects on crop yields because of the compensatory effects of climatic changes and environmental stresses.

Unfortunately, the data for woody plants are much more limited than those for herbaceous plants and are based largely on seedling experiments that lasted only for a few weeks or months. While seedling quality and establishment are important, experiments lasting, at most, one growing season are too short to permit safe generalizations concerning what will occur later in development. Sionit and Kramer (1984) summarized the results of 15 of these short-term experiments on woody plants and reported the following general conclusions with respect to growth.

- Dry weight, stem diameter, and height of seedlings generally are increased by CO_2 concentrations in the range of 400 to

700 ppm.

- CO_2 concentrations above 500 to 600 ppm usually produce little additional growth and sometimes even cause a decrease.
- Seedlings of various species react differently to increases in CO_2 concentration, making it necessary to study each species individually.
- A high concentration of CO_2 seems to have morphological effects, causing increasing branching, leaf area, and leaf thickness in some but not all species.
- The competitive capacity of seedlings of various species is likely to be affected differently by an increase in CO_2 concentration.

Fortunately, there seem to be some similarities in the reaction to high CO_2 between C_3 herbaceous and woody plants. This was shown in a study at North Carolina State University by Rogers and his associates (1983) in which corn (*Zea mays* L.), soybeans (*Glycine max* L. Merr.), and sweetgum (*Liquidambar styraciflua* L.) were grown outdoors in open-topped containers and maintained at various CO_2 concentrations for 12 or 13 weeks. They found that stomatal conductance decreased about 50% in all three species as the CO_2 concentration increased from ambient to 910 ppm. At the same time the rate of net photosynthesis increased 65% for sweetgum and about 70% for soybean.

The failure of corn to show any increase relates to its C_4 carbon-fixation pathway. Corn, sugarcane, and a number of other plants have what is called the Hatch-Slack or C_4 carbon pathway because CO_2 is fixed initially into four-carbon organic acids in the leaf mesophyll cells by an enzyme, phosphoenolpyruvate carboxylase (PEP carboxylase), which is saturated at the present atmospheric concentration of CO_2 and is little affected by further increases. Also, in C_4 plants the organic acid produced by carboxylation in the mesophyll cells diffuses to the bundle sheath cells and is decarboxylated, producing a high concentration of CO_2 that increases the rate of the final conversion to sugars by the Calvin cycle or C_3 pathway. This results in a very low apparent mesophyll resistance for CO_2 in C_4 plants, making them less responsive than C_3 plants to an increase in atmospheric CO_2 concentration.

However, the important point here is that the behavior of the two C_3 plants, herbaceous soybean and woody sweetgum, is surprisingly similar. This encourages extrapolation from herbaceous plants to woody seedlings until more data become available for the latter. For example, in the experiments of Rogers et al. (1983), the dry weight of both loblolly pine and sweetgum increased about 40%

at 910 ppm. In other experiments by Tolley and Strain (1984a) and Sionit et al. (1985), dry weights of both species also increased significantly at CO_2 concentrations of 500 to 1000 ppm (Table 1).

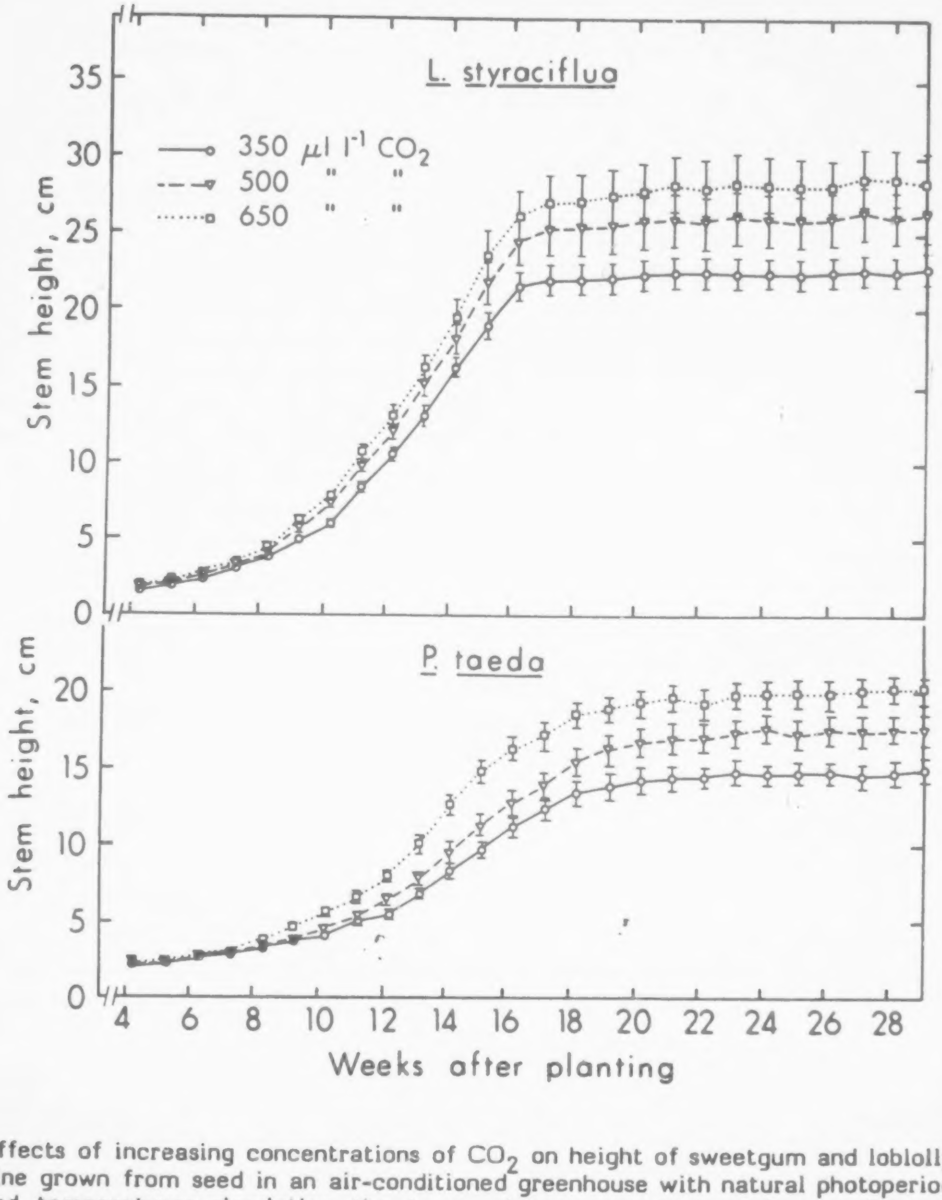
Long-term experiments are now in progress in the Duke University Phytotron. Seedlings of loblolly pine (*Pinus taeda* L.) and sweetgum were germinated and grown in controlled-environment greenhouses at 350, 500, and 650 ppm of CO_2, with temperature regimes following those outside and with natural photoperiods and light regimes. At the end of the first growing season the dry weights of sweetgum seedlings were over 40% greater and those of loblolly pine were nearly 60% greater at 500 than at 350 ppm of CO_2 (Table 1). However, no significant increase in dry weights occurred at 650 ppm of CO_2 over the weights at 500 ppm. Root-shoot ratios were not significantly increased by CO_2 enrichment in either species. Stem height increased with increasing CO_2 in both species, and sweetgum was taller than loblolly pine at all concentrations (Figure 1). Sweetgum seedlings produced significantly more leaves at the high CO_2 concentrations than at 350 ppm (Figure 2), probably because they produced more branches. Leaf senescence began about the same time in 350 and 650 ppm of CO_2.

The data in Table 2 show that all the organs of loblolly pine seedlings continued to increase in dry weight during the winter. The rate of net photosynthesis of pine needles was greater at 650 ppm of CO_2 than at lower CO_2 concentrations, but the percent increase in dry weight was no greater at 650 than at 350 ppm. Sweetgum seedlings showed no important changes in dry weight over winter if the total dry weight was corrected for leaf loss (Table 3). Data from another winter are needed to establish whether the small loss in dry weight at 350 ppm and the gain at 650 ppm are real.

GROWTH EFFECTS OF HIGH CO_2 CONCENTRATIONS

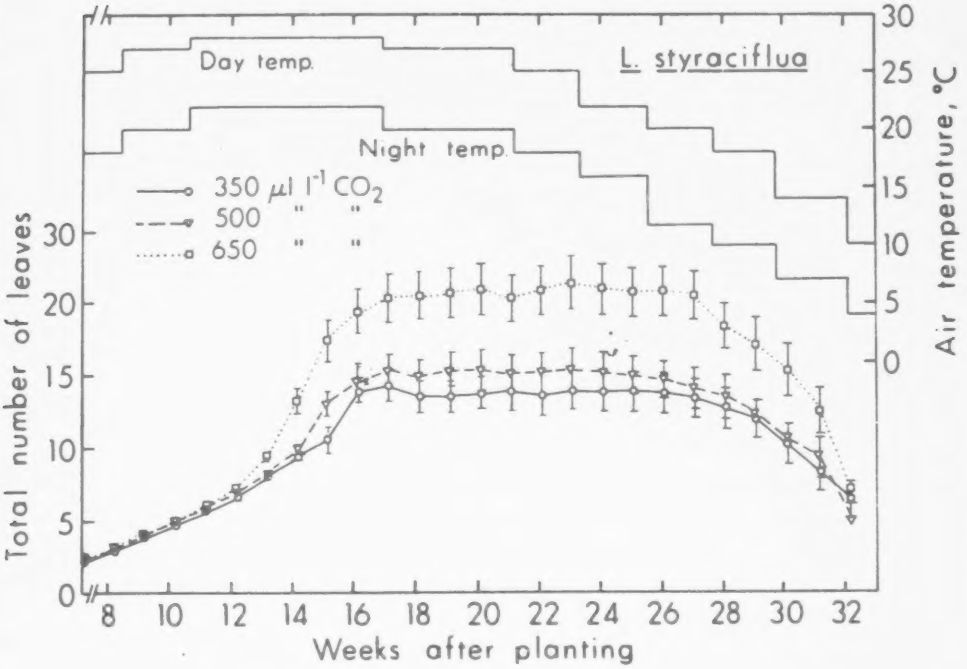
The data available suggest that doubling the atmospheric CO_2 concentration will increase the growth of tree seedlings of at least some species as much as it increases the growth of herbaceous plants, if other environmental factors are not severely limiting. It is a general principle that the quantity and quality of growth are controlled by the interaction of the hereditary potential (the genome) and the environment, operating through basic physiological processes. Environmental stresses, such as drought or unfavorable temperature, and silvicultural treatments, such as thinning, pruning, and fertilization, affect growth by modifying the physiological processes and conditions that directly control growth

Figure 1



Effects of increasing concentrations of CO_2 on height of sweetgum and loblolly pine grown from seed in an air-conditioned greenhouse with natural photoperiod and temperatures simulating the two-week average obtained from a 30-year temperature record. The seedlings became dormant and the sweetgum shed their leaves by about week 32. Concentration of CO_2 as microliters per liter (μ 1 1^{-1}) is equivalent to ppm. Figures 1 and 2 are based on measurements of 15 seedlings at each date. (From data of Sionit et al., 1985.)

Figure 2



Temperature regime and effects of increased concentration of CO_2 on numbers of leaves on sweetgum seedlings in the experiment described under Figure 1. The increase in leaf number at 650 $\mu l\ l^{-1}$ (ppm) was correlated with the increase in number of branches. (From data of Sionit et al., 1985.)

Table 1
Effects of Atmospheric Carbon Dioxide Enrichment on Growth
of L. Styraciflua (Sweetgum) and P. Taeda (Loblolly Pine)
at 32 Weeks after Planting
(end of first growing season)

Species	Carbon dioxide concentration (ppm)	Stem weight (g)	Leaf weight (g)	Root weight (g)	Root-shoot ratio	Total weight (g)	Percent increase in total weight
L. styraciflua	350	2.1 a	1.5a	6.3 a	1.7 ab	9.9 a	
	500	3.4 b	1.6 ab	9.2 b	1.8 b	14.2 b	43.4
	650	3.7 b	2.0 b	8.6 ab	1.5 a	14.3 b	44.4
P. taeda	350	0.4 a	1.4a	2.1 a	1.2 a	3.9 a	
	500	1.0 b	2.3 b	2.9 b	0.9 a	6.2 b	58.9
	650	0.8 b	2.1 b	3.2 b	1.1 a	6.1 b	56.4

Means followed by the same letter within a column for each species are not significantly different at the 5% level of probability. Values are means of measurements on 15 seedlings. From Sionit et al., 1985.

Table 2
Effects of Atmospheric Carbon Dioxide Enrichment on Growth
of L. Styraciflua (Sweetgum) and P. Taeda (Loblolly Pine)
at 48 Weeks after Planting
(end of first dormancy period)

Species	Carbon dioxide concentration (ppm)	Stem weight (g)	Leaf weight (g)	Root weight (g)	Root/shoot ratio	Total weight (g)
L. styraciflua	350	1.8 a	--	5.9 a	3.3 b	7.7 a
	500	3.0 b	--	9.2 b	3.1 ab	12.3 b
	650	3.5 b	--	9.5 b	2.8 a	13.0 b
P. taeda	350	1.0 a	2.2 a	4.1 a	1.3 a	7.3 a
	500	1.2 a	2.5 a	4.8 ab	1.3 a	8.5 ab
	650	1.5 a	3.3 b	6.5 b	1.4 a	11.3 b

Means followed by the same letter within a column for each species are not significantly different at the 5% level of probability. From Sionit et al., 1985.

Table 3
Changes over the Winter Period in Total Dry Weight of L. Styraciflua (Sweetgum) and P. Taeda (Loblolly Pine) Seedlings Grown at Three Atmospheric Carbon Dioxide Concentrations[1]

Species	Carbon dioxide concentration (ppm)	Percent change in total dry weight	Net photosynthesis (mg g-1 DW h-1)[2]
L. styraciflua[3]	350	-8.4	-
	500	-2.4	-
	650	+5.7	-
P. taeda	350	+87.2	1.4
	500	+37.1	1.9
	650	+85.2	3.4

[1] From data of Sionit et al., 1984.

[2] Milligrams per gram of dry weight per hour.

[3] Corrected for leaf loss.

(Figure 3).

Carbon dioxide is no exception to this general principle, so its effects on growth must be explained in terms of its effects on important physiological conditions and processes including stomatal conductance, photosynthesis, carbohydrate partitioning, and the plant's water economy. An increase in CO_2 concentration directly affects stomatal conductance and photosynthesis and indirectly affects transpiration and other processes discussed later.

Direct Effects

Experimental evidence indicates the following direct effects of CO_2 buildup in tree physiology.

Stomatal Conductance

In most experiments, increasing the CO_2 concentration causes partial closure of stomata, decreasing the conductance for CO_2 and water vapor. In one outdoor experiment the decrease amounted to 40% for sweetgum when the CO_2 concentration was doubled (Rogers et al., 1983). In a growth chamber experiment stomatal conductance was decreased about 50% in sweetgum, but not at all in loblolly pine, by increasing the CO_2 concentration from 350 to 675 ppm (Tolley, 1982). Beadle et al. (1979) reported that the stomatal conductance of Sitka spruce (*Picea sitchensis*) was unaffected by CO_2 concentrations in the range of 20 to 600 ppm. The reasons for differences among species in stomatal response are unknown, probably because the exact mechanism by which high ambient concentrations of CO_2 decrease stomatal aperture is not fully understood.

The complex relationships among stomatal conductance, rate of CO_2 uptake, and transpiration are shown in Figure 4 for Eastern cottonwood (*Populus deltoides*) seedlings subjected to various concentrations of CO_2 for two weeks. Stomatal conductance decreased about 25% between 300 and 600 ppm; transpiration also decreased about 25% but photosynthesis increased about 40%.

Both inward diffusion of CO_2 and outward diffusion of water vapor are affected by stomatal aperture or conductance. Thus it seems paradoxical that photosynthesis can increase when stomatal conductance and transpiration are decreasing. However, the paradox can be explained in part by the differences in resistances to water and CO_2 movement, shown in Table 4, and in part by the increase in CO_2 concentration within leaves. The major resistance to the escape of water vapor from leaves is the stomata, and an

Figure 3

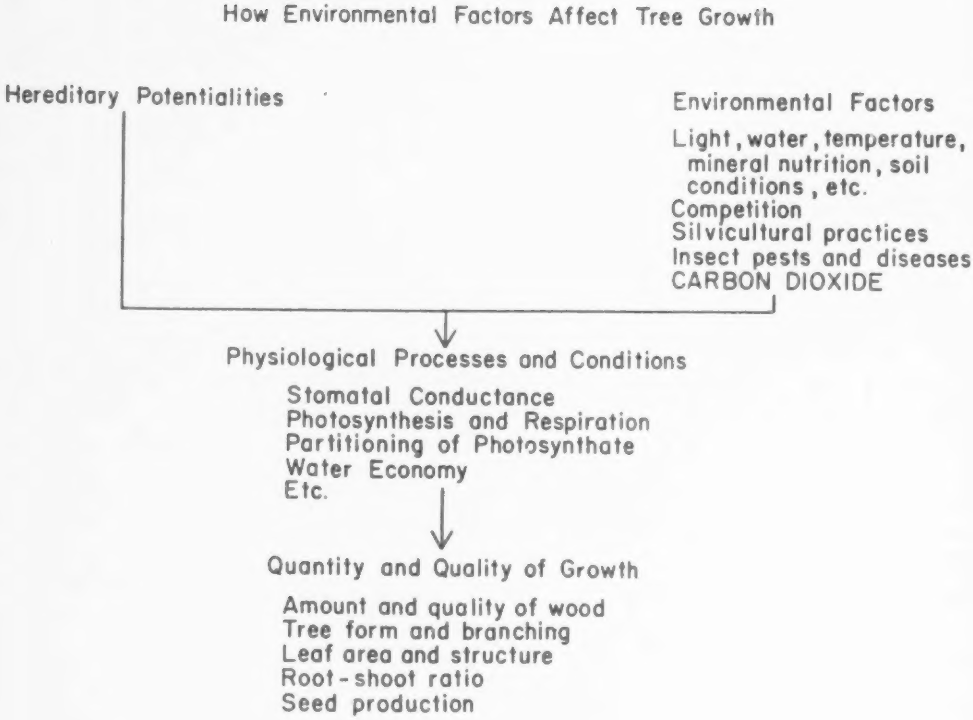
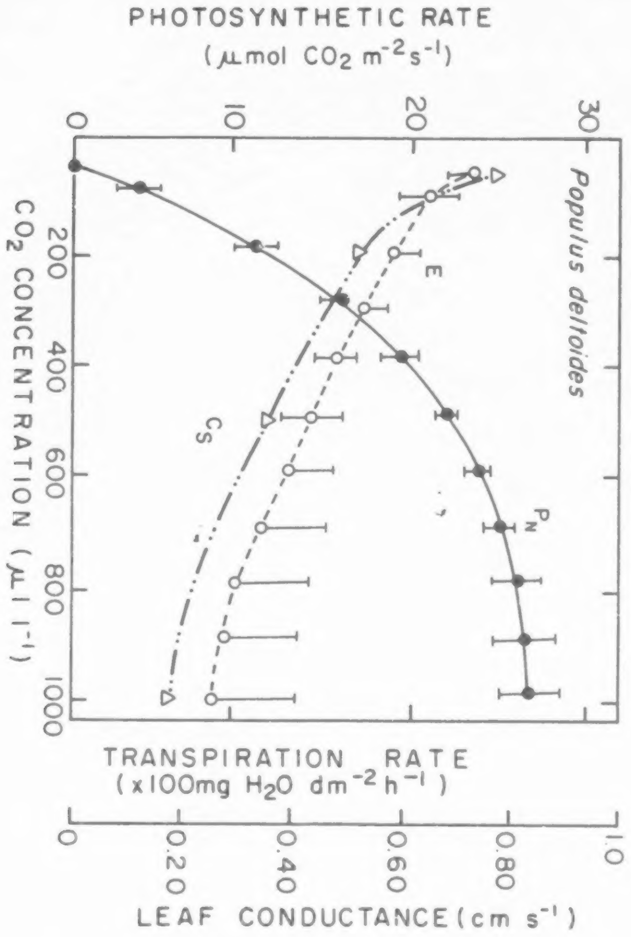

How Environmental Factors Affect Tree Growth
Hereditary Potentialities
Environmental Factors
Light, water, temperature, mineral nutrition, soil conditions, etc.
Competition
Silvicultural practices
Insect pests and diseases
CARBON DIOXIDE
Physiological Processes and Conditions
Stomatal Conductance
Photosynthesis and Respiration
Partitioning of Photosynthate
Water Economy
Etc.
Quantity and Quality of Growth
Amount and quality of wood
Tree form and branching
Leaf area and structure
Root-shoot ratio
Seed production

Diagram showing how environmental factors interact with hereditary potentialities to modify the physiological processes and conditions that control the quantity and quality of growth.

Figure 4



Photosynthesis (P_n), transpiration (E), and leaf conductance (C_s) as functions of CO_2 concentration. (Adapted from Regehr et al., 1975.)

Table 4
Effects of Partial Closure of Stomata on Rates of Transpiration and Photosynthesis

	Air and stomatal resistance (sec cm^{-1})^2		Internal or mesophyll resistance (sec cm^{-1})		Total resistance (sec cm^{-1})	Reduction in conductance (percent)
H_2O						
Stomata open	2.3	+	0	+	2.3	50
Stomata partly closed	4.6	+	0	+	4.6	
CO_2						
Stomata open	3.7	+	6.1	+	9.8	27
Stomata partly closed	7.4	+	6.1	+	13.5	

[1] From data of Cooke and Rand (1980).

[2] Seconds per centimeter.

increase in stomatal resistance decreases transpiration proportionately. However, there are additional resistances to the movement of CO_2 to the chloroplasts and its fixation into carbohydrates. These are known collectively as the apparent mesophyll resistance, and it is relatively high in trees and in those crop plants possessing the C_3 photosynthetic pathway. Thus a 50% increase in stomatal resistance decreases transpiration about 50%, but decreases photosynthesis much less because it is only part of the total resistance to CO_2 movement. Also, for reasons discussed in the next section, the increase in stomatal resistance is compensated in C_3 plants by the increased internal CO_2 concentration at high external concentrations. This difference in effect of partial closure of stomata on diffusion of water vapor and CO_2 also is the basis for the use of antitranspirants that cause stomatal closure (Kramer, 1983).

Photosynthesis

Most crop plants have the C_3 or Calvin cycle pathway of photosynthesis, in which CO_2 is fixed in three-carbon phosphoglyceric acid by the enzyme ribulose bisphosphate carboxylase (RuBP carboxylase). This enzyme has an affinity for both CO_2 and O_2 and functions both as a carboxylase and as an oxygenase. The oxygenase activity is responsible for photorespiration, which according to various authors can use 15 to 50% of the carbon fixed by photosynthesis in C_3 plants (Gifford et al., 1984). However, an increase in ambient CO_2 concentration results in an increase in CO_2 concentration within leaves, increasing the rate of carboxylation relative to oxygenase activity, which leads to increased net photosynthesis.

Increase in ambient CO_2 concentration also tends to compensate for the inhibitory effects of shading (Tolley and Strain, 1984a) and high temperature. Although the maximum absolute enhancement of photosynthesis by higher concentrations of CO_2 is at saturating light intensities, the maximum relative increase occurs at low intensities (Pearcy and Bjorkman, 1983), where the increased rate of photosynthesis resulting from a higher CO_2 concentration at the carboxylating sites is most important relatively. Thus the increase in atmospheric CO_2 concentration may be most important for photosynthesis in the lower part of tree canopies and for vegetation on the forest floor. Also the optimum temperature for photosynthesis of at least some C_3 plants is increased significantly by an increase in concentration of CO_2 because of the speedup in carboxylation rate and slowdown in photorespiration. This may become more important if increase in the atmospheric CO_2 concentration causes a significant rise in temperature.

Short- versus Long-Term Effects on Photosynthesis. Short-term measurements of photosynthesis, such as those shown in Figure 4, are not always good indicators of the effects of prolonged exposure. Kramer (1981) cited instances in which the rate of photosynthesis of herbaceous species exposed to high concentrations of CO_2 decreased over time; this was observed in loblolly pine and sweetgum seedlings by Tolley and Strain (1984a). In some, but not all, experiments the reduction in rate per unit of leaf area was compensated by increase in leaf area and/or leaf thickness (Tolley and Strain, 1984a; Sionit et al., 1985). One reason for the reduction in rate at high CO_2 concentrations may be feedback inhibition caused by accumulation of carbohydrate (Clough et al., 1981). Another possibility is actual injury to chloroplasts by accumulation of starch, causing distortion of membranes and inhibition of electron transport. This has been observed in several herbaceous species (Hofstra and Hesketh, 1975; Cave et al., 1981; Wulff and Strain, 1982). It also is possible that a high CO_2 concentration reduces the activity or amount of carboxylating enzyme in some plants (Wong, 1979). Thus it is unwise to attempt to extrapolate from short-term experiments to long-term effects of exposure to high concentrations of CO_2.

Photosynthesis and Biomass. The relationship between photosynthesis and biomass at high concentrations of CO_2 was discussed by Kramer (1981). Because biomass depends on photosynthesis, there is a tendency to assume that the chief effect of increasing CO_2 concentration is through increase in the rate of photosynthesis, but the indirect effects may also be important. Biomass is not necessarily closely correlated with rate of photosynthesis because it depends not only on rate per unit of leaf area but also on total leaf area and leaf duration as well as the length of time during which leaves carry on photosynthesis. The latter may become particularly important with respect to competition between evergreen and deciduous trees in regions with mild winters.

It has been pointed out (Figure 4) that the rate of photosynthesis usually increases curvilinearly at intermediate CO_2 concentrations and tends to level off or even decrease at much higher concentrations. However, in some experiments this was compensated for by an increase in leaf area and/or leaf thickness. Sweetgum seedlings grown at high CO_2 concentrations showed some increase in leaf area after 13 weeks, compared to those at 350 ppm, although not after 32 weeks. However, the seedlings showed a significant increase in weight per unit of leaf area at 32 weeks, and this probably indicated an increase in amount of photosynthetic tissue per unit of leaf surface (Nobel, 1980). Loblolly pine also produced a greater weight of needles at the higher concentration of CO_2. Some of these data are shown in Table 1.

Indirect Effects

Increasing the concentration of CO_2 in the atmosphere has various indirect effects not yet fully evaluated.

Partitioning of Carbohydrates

The ultimate success of both field and forest crops depends on partitioning the maximum amount of photosynthate into a merchantable product. In forest trees this usually is bole wood, and the increase in branching observed in sweetgum seedlings probably would be undesirable. The increases in branching, leaf area, and leaf thickness in seedlings grown in high concentrations of CO_2 are caused by changes in the amount of carbohydrate partitioned into various structures, but the causes of these changes are not known.

Although an increase in root-shoot ratio might be expected to accompany an increase in photosynthesis, and has been observed in some herbaceous plants (Sionit et al., 1982, for example), it has not been observed in tree seedlings. No significant differences in root-shoot ratios at various concentrations of CO_2 developed in either pine or sweetgum seedlings during an entire growing season in the experiments of Sionit et al. (1985), for which data are given in Table 1. However, the ratio of roots to shoots was much greater in sweetgum than in loblolly pine at all concentrations of CO_2 (Table 1). Also the root-shoot ratio of loblolly pine seedlings increased substantially over winter at all concentrations of CO_2. The number of branches doubled at 650 ppm on sweetgum seedlings but increased only slightly on loblolly pine seedlings. Although the increase in number of branches on sweetgum seedlings probably represents an undesirable diversion of photosynthate from stem growth, the stem diameter of sweetgum seedlings was significantly greater at the higher concentrations of CO_2. The proportion of the total dry weight occurring in leaves was not consistently affected by increasing concentrations of CO_2, although leaf weight was increased in both species.

In general the overall dry weight of all plant parts increased without any important change in size of any one organ relative to that of another. Perhaps this demonstrates that the correlation in relative size that exists among various organs of a plant is so strong that only a severe stress, such as severe water stress, heavy shading, or serious lack of nitrogen, is likely to cause important changes in proportions of roots to shoots or of leaves versus roots and stems. In some crop plants, the amount of photosynthate partitioned into seeds is important, but there is no information concerning the effects of increasing the CO_2 concentration on flowering and seed production of forest trees. If it causes earlier flowering or a significant increase in seed production, it might be useful in tree-breeding experiments.

Water Relations

Increasing the concentration of CO_2 causes partial closure of stomata and reduces the rate of transpiration. This should postpone dehydration and maintain adequate levels of leaf water potential and cell turgor longer during drought in high than in low concentrations of CO_2. In some short-term experiments this has occurred. In one series of experiments, when seedlings of sweetgum and loblolly pine were water stressed in growth chambers, the water potential was higher in seedlings growing at 1000 ppm than in those growing at 350 ppm, at both high and low irradiances (Tolley, 1982). However, in an unpublished experiment, Sionit found that, although transpiration and stomatal conductance of sweetgum seedlings were reduced at 650 ppm compared with 350 ppm of CO_2, the leaf water potential was decreased to the same extent by water stress at both concentrations of CO_2. Also, no significant differences in water potential were found in loblolly pine seedlings grown at normal and high concentrations of CO_2 and then subjected to water stress. Thus the exact response to water stress in high concentrations of CO_2 seems to depend on presently unidentified factors.

It should be emphasized that stomatal closure merely postpones dehydration. However, there is a possibility that the increased carbohydrate content of leaves in a high concentration of CO_2 may result in increased tolerance of dehydration by causing osmotic adjustment. This means that the osmotic potential decreases more than can be explained by the decrease in water content. The decrease in osmotic potential enables the cells to remain turgid and the stomata to remain at least partially open to a lower water potential. Sionit et al. (1981) found that osmotic adjustment occurs in wheat, but it has not yet been sought for in woody plants subjected to water stress in a high concentration of CO_2. So far as is known, a high concentration of CO_2 confers no increased protoplasmic toleration of dehydration.

Water-Use Efficiency

"Water-use efficiency" (WUE) is a term widely used today in discussions of plant-water economy (*see* Sinclair et al., 1984). As used by physiologists, the term refers to units of CO_2 fixed per unit of water transpired. On this basis, an increase in CO_2 concentration is likely to materially increase WUE because it tends to decrease transpiration and increase photosynthesis. Downton et al. (1980) reported that doubling the CO_2 concentration doubled the WUE of creosote bush (*Larrea divaricata*) and oleander (*Nerium oleander*) and that the differences were maintained for two months. Rogers et al. (1983) reported that the WUE of sweetgum, corn, and soybeans growing in open-topped containers in the field was more than doubled at 910 ppm, and Tolley (1982) observed that the WUE of sweetgum seedlings was more than doubled at 1000 ppm of CO_2 in growth chambers.

Thus, in terms of the ratio of leaf photosynthesis to leaf transpiration, there appears to be a dramatic increase in WUE. However, Sinclair et al. (1984) discussed the difficulties in extrapolating from leaves to leaf canopies, and it is uncertain whether conclusions based on essentially instantaneous measurements made on single leaves can be extrapolated to forest canopies without considerable qualifications. It seems possible that leaves at lower levels in a canopy may have a WUE quite different from fully exposed leaves. Some of the uncertainties encountered in estimating transpiration within a forest canopy are discussed by Kaufmann (1984), and similar uncertainties exist with respect to photosynthesis. Furthermore, if there is an increase in leaf area, this may partially offset the decreasing rate of transpiration. Also, for practical purposes the WUE of a stand depends on the relationship between wood produced and total water used in evaporation and transpiration. The total water used often is expressed for watersheds as the difference between precipitation and runoff. How good the correlation is between WUE of a forest stand and that based on physiological measurements of a single leaf remains to be determined.

INTERACTION OF CO_2 CONCENTRATION WITH OTHER LIMITING FACTORS

In the forest, tree growth usually is limited by a combination of stresses. At present the suboptimal concentration of atmospheric

CO_2 always is limiting, but, in addition, growth often is limited by drought, mineral deficiencies, shade, and unfavorable temperatures, either singly or in combination. The concept of limiting factors sometimes is incorrectly invoked to argue that if growth already is limited by one suboptimal factor it cannot respond to an increase in another suboptimal factor, such as CO_2 concentration. This is not true unless the other stresses are very severe. According to Mitscherlich's concept of limiting factors, if growth is limited simultaneously by several factors, the response to an improvement in any one factor will be approximately proportional to the degree of deficiency of that factor.

An increase in CO_2 concentration will produce a measurable increase in growth of both woody and herbaceous plants suffering from water, temperature, or mineral deficiency stress. For example, Tolley and Strain (1984b) found that even with limiting irradiance (250 μmol m^{-2} s^{-1}) and water stress, doubling the ambient CO_2 concentration produced a 17% increase in dry weight of sweetgum seedlings and a small increase in pine seedlings, as shown in Table 5. However, in the absence of water or light stress, doubling the ambient CO_2 concentration produced more than twice as much increase in dry weight as for stressed plants. Thus, while an increase in CO_2 concentration increased growth of water- and light-stressed seedlings, it produced a greater increase in unstressed seedlings. Other examples of such interactions will be discussed next.

Water Stress

Probably water stress is the factor most often limiting tree growth, both directly by stomatal and nonstomatal inhibition of photosynthesis and indirectly by reducing cell expansion and decreasing leaf area and shoot and root elongation. In general, cell enlargement and growth are inhibited by water stress before photosynthesis is much reduced (Boyer, 1970). The reduced sink capacity caused by reduced growth is likely to result in accumulation of carbohydrate and reduction in photosynthesis by feedback inhibition, regardless of CO_2 concentration. Also, because roots are subjected to less water stress than shoots, roots are likely to make more growth in mildly water-stressed plants, resulting in an increased root-shoot ratio (Sharp and Davies, 1979). If water stress reduces leaf expansion early in the growing season, this may reduce the benefit expected from increased CO_2 concentration. Thus, although in theory doubling the CO_2 concentration should reduce injury from drought, it is uncertain how much it

Table 5
Compensatory Effects of Increased Carbon Dioxide Concentration on Dry Weight of Stressed Sweetgum and Loblolly Seedlings[1]

Species	Carbon dioxide (ppm)	Light (μmol m^{-2}s^{-1})[2]	Water potential (bars)	Total dry weight (g)	Percent increase
L. styraciflua	350	250	-22	0.81	
	675	250	-10	0.95	17
	675	1000	-22	1.06	30
	675	1000	-3	1.15	42
P. taeda	350	250	-18	0.36	
	675	250	-18	0.39	8
	675	1000	-24	0.51	41
	675	1000	-7	0.62	72

[1] n = 10 (Tolley and Strain, 1984b).

[2] Micromoles per square meter per second.

will compensate for the effects of the severe droughts characteristic of much of the United States.

The only data available on the interaction of water stress and CO_2 on tree seedlings are those in Table 5, which indicate that doubling the CO_2 concentration compensated to some degree for water and light stress either singly or in combination. The data also suggest that low irradiance is more limiting to loblolly pine that to sweetgum.

Temperature

The compensating effects of increased CO_2 for high temperatures were discussed briefly in relation to photosynthesis and are further discussed by Leverenz and Lev (this volume). However, a few special examples should be mentioned. Kriedemann et al. (1976) reported that placing grapes and several other kinds of woody plants in a CO_2 concentration of 1200 to 1300 ppm increased their growth and tolerance of temperatures in the range of 37° to 40°C (98.5° to 104°F). Only guava, among a half dozen plants tested, showed no improvement in growth. The grapes were exposed to these abnormally high temperatures for 3 to 6 months to eliminate viruses. Sionit et al. (1981) reported that okra (*Abelmoschus esculentus* L. Moench) is unproductive when grown at temperatures lower than 26/20°C (79/68°F) (day/night) in ambient CO_2, but in a concentration of 1000 ppm of CO_2 it yielded well at 20/14°C (68/57°F) (day/night). Thus high concentrations of CO_2 seem to have considerable compensatory effects for both high and low temperatures, although the effects probably will be greater at high than at low temperatures.

Light

In a comparison of growth of loblolly pine and sweetgum seedlings in a controlled environment, Tolley and Strain (1984a) found that sweetgum far outgrew loblolly pine at a CO_2 concentration of 675 ppm at a low irradiance. Sweetgum grew 86% taller and produced 31% more leaf area and 28% more biomass at an irradiance of 250 μmol m^{-2} s^{-1} and 675 ppm of CO_2 than at 1000 μmol m^{-2} s^{-1} and 350 ppm of CO_2. In contrast, loblolly pine seedlings grew only 11% taller and produced less biomass and leaf surface with low irradiance and a high concentration of CO_2 than with high irradiance and 350 ppm of CO_2.

It appears that the compensatory effects of CO_2 for low irradiance may have differential effects on the success of seedlings of some species competing on the forest floor. This deserves careful study because in the long term it might cause changes in species composition of forests and other ecosystems.

Mineral Deficiencies

No data are available for woody plants, but the data from experiments with soybeans and wheat indicate that doubling the CO_2 concentration compensates at least in part for deficiencies in mineral nutrients (Sionit et al., 1981; Sionit, 1983). Patterson and Flint (1982) found that doubling the CO_2 concentration increased the growth of soybeans and several weeds, even when growth was limited by mineral deficiencies. It seems likely that the ratio of carbon to nitrogen will be higher in plants grown with a high atmospheric concentration of CO_2, although the data available are equivocal (Sionit et al., 1981; Pearcy and Bjorkman, 1983). However, it can be expected that if dry-matter production is increased the use of nitrogen and mineral nutrients also will increase. Thus, it seems safe to predict that more nitrogen and in some areas more phosphorus will be required for woody plants to obtain maximum benefits from the CO_2 increase.

Because of the complexity of these interactions, the differences among plants of various species, and the variations in weather, it is very difficult to predict the effects of CO_2 buildup on a particular crop or forest stand in a particular year (Wong, 1979; Osmond et al., 1980). As mentioned earlier, Waggoner (1984) expects relatively small changes in crop yields because the increases in dry-matter production predicted from CO_2 effects on physiological processes are likely to be counterbalanced by unfavorable climatic changes. It seems probable that for many years the short-term perturbations from normal rainfall and temperature are likely to have more effect on tree growth than the predicted climatic changes caused by the increasing concentration of CO_2 in the atmosphere.

MISCELLANEOUS EFFECTS OF INCREASING CARBON DIOXIDE CONCENTRATION

A few other effects of high CO_2 must be considered.

Flowering and Seed Production

The effects of an increasing concentration of atmospheric CO_2 on flowering and seed production are important for the natural regeneration of forests as well as for selection and breeding programs. Unfortunately, nothing is known about the effects of CO_2 concentration on the reproductive processes of trees, but if differences develop among species this might affect the species composition of forests in the long term. Zangerl and Bazzaz (1984) stated that the relative proportions of biomass partitioned into seed were affected differently in several herbaceous annuals. However, observations are needed on trees at every stage of reproduction, from flower initiation through flowering, pollination, and fertilization to the quantity and quality of seed produced. It should be possible to study the effects of CO_2 concentration on reproduction of some species by grafting branches from reproductive-age trees on seedlings growing in controlled environments.

Flowering and fruiting generally deplete the carbohydrate reserves of trees, and there is some evidence that treatments which increase the carbon-nitrogen ratio in fruit trees increase flowering (Kramer and Kozlowski, 1979). Because high CO_2 levels generally result in high ratios of carbon to nitrogen in leaves, atmospheric buildup might case earlier flowering and increased seed production. The use of enhanced CO_2 concentration for this purpose in tree-breeding experiments needs to be investigated.

Seedling Establishment and Stand Composition

Although an experimental high concentration of CO_2 has increased the rate of emergence and early growth of mountain laurel (*Kalmia*) seed (Heichel and Jaynes, 1974), it is doubtful that doubling the atmospheric concentration will have any significant effect on seed germination because the concentration already is much higher in soil than in air. However, numerous greenhouse and growth-chamber experiments indicate that after germination seedling growth is increased by the increase in leaf area and in rate of photosynthesis per unit of leaf area. This suggests that an increased concentration of CO_2 might increase growth of container-grown seedlings in greenhouses or other enclosures.

A buildup of atmospheric CO_2 is projected to change the composition of annual plant communities, especially where C_3 and C_4 plants compete (Bazzaz and Carlson, 1984). In general the competitive capacity of C_3 relative to C_4 plants should be increased by increasing concentrations of CO_2 (Strain and Bazzaz, 1983). However, all forest trees have the C_3 carbon pathway, and the differences in competitive capacity among species are likely to be smaller among trees in forests than in communities of annual plants. Thus long-term experiments spanning a decade may be necessary to demonstrate whether interspecific differences are important to foresters.

As mentioned earlier, high concentrations of CO_2 increase drought and shade tolerance, and this should increase growth of seedlings on the forest floor. If important differences in reaction to CO_2 occur among competing species, this may produce long-term changes in the composition of naturally regenerated forest stands.

Wood Quality

The effects of rising ambient CO_2 concentration on wood quality are unknown. In the only published experiment, exposure of pine and sweetgum seedlings to high concentrations of CO_2 caused no change in wood density of loblolly pine and a small increase in density of sweetgum (Rogers et al., 1983). In another unpublished experiment, there were small increases in density of wood from seedlings of both species. Data are needed from older trees.

Tolerance of Air Pollution

Increasing concentration of CO_2 is likely to decrease injury from air pollution because partial closure of stomata should reduce the entrance of pollutants into leaves. Green and Wright (1977) also reported that elevated CO_2 caused a significant increase in photosynthesis of ponderosa pine damaged severely by air pollution. Carlson and Bazzaz (1982) reported that a high concentration of CO_2 decreased injury to plants of several C_3, herbaceous species from fumigation with sulfur dioxide (SO_2).

Root Reactions

The increase in atmospheric CO_2 will have no direct effect in soil, where the concentration normally is far above 1,000 ppm. However, if the supply of carbohydrates to roots is increased this might increase mycorrhizal development and nitrogen fixation by roots of leguminous trees.

Diseases and Insect Pests

Changes in carbohydrate-nitrogen ratios of plants and changes in rainfall and temperature patterns are almost certain to change the kinds and severity of diseases and pests. For example, a drier climate and more water stress are likely to increase attacks by boring insects. In a preliminary study in the Duke University Phytotron (Lincoln et al., 1984), larvae of the soybean looper (*Pseudoplusia includens*) ate more tissue per larva on leaves of soybeans grown at 650 ppm of CO_2 than on those of plants grown in a 350-ppm atmosphere. The difference in rate of feeding was correlated with the difference in carbon-nitrogen ratio and was greater in leaves with a high carbon-nitrogen ratio. As elevating CO_2 usually tends to increase the ratio of carbon to nitrogen, the greater leaf area at higher concentrations of CO_2 might be offset by higher herbivory. This research area deserves more investigation.

ACKNOWLEDGMENTS

The research on woody plants by N. Sionit, L. C. Tolley, and B. R. Strain cited in this paper was supported by National Science Foundation grants no. DEB78-23640 and BSR82-15533. That of Rogers and his associates (1983) was supported by Department of Energy interagency grants through the U.S. Department of Agriculture.

REFERENCES

Bazzaz, F. A., and R. W. Carlson. 1984. The response of plants to elevated CO_2. I. Competition among an assembly of annuals at different levels of soil moisture. *Oecologia* (in press).

Beadle, C. L., P. G. Jarvis, and R. E. Neilson. 1979. Leaf conductance as related to xylem water potential and carbon dioxide concentration in Sitka spruce. *Physiol. Plant.* 45, 158-166.

Boyer, J. S. 1970. Differing sensitivity of photosynthesis to low leaf water potentials in corn and soybean. *Plant Physiol.* 46, 236-240.

Carlson, R. W. and F. A. Bazzaz. 1982. Photosynthetic and growth response to fumigation with SO_2 at elevated CO_2 for C_3 and C_4 plants. *Oecologia* 54, 50-54.

Cave, G. H., L. Tolley, and B. R. Strain. 1981. Effects of carbon dioxide enrichment on chlorophyll content, starch content and starch grain structure in *Trifolium subterraneum* leaves. *Physiol. Plant.* 51, 171-174.

Clough, J. M., M. M. Peet, and P. J. Kramer. 1981. Effects of high atmospheric CO_2 and sink size on rates of photosynthesis of a soybean cultivar. *Plant Physiol.* 67, 1007-1010.

Cooke, J. R. and R. H. Rand. 1980. Diffusion resistance models, p. 94-121. *In* J. D. Hesketh and J. W. Jones (ed.), *Predicting Pho-*

tosynthesis for Ecosystem Models, vol. 1. CRC Press Inc., Boca Raton, Fl.

Downton, W. J. S., O. Bjorkman, and C. S. Pike. 1980. Consequences of increased atmospheric concentrations of carbon dioxide for growth and photosynthesis of higher plants. *In* G. I. Pearman (ed.), *CO_2 and Climate, Australian Research.* CSIRO, Australian Academy of Science, Canberra, Australia.

Gifford, R. M., J. H. Thorne, W. D. Hitz, and R. T. Giaquinta. 1984. Crop productivity and photoassimilate partitioning. *Science* 225, 801-808.

Green, K., and R. D. Wright. 1977. Field responses of photosynthesis to CO_2 enhancement in ponderosa pine. *Ecology* 58, 687-691.

Heichel, G. H., and R. A. Jaynes. 1974. Stimulating emergence and growth of *Kalmia* genotypes with carbon dioxide. *Hortscience* 9, 60-62.

Hofstra, G., and J. D. Hesketh. 1975. The effects of temperature and CO_2 enrichment on photosynthesis in soybean, p. 71-80. *In* R. Marcelle (ed.), *Environmental and Biological Control of Photosynthesis.* J. Junk, The Hague.

Kaufmann, M. R. 1984. Em-CWU, a canopy model for determining transpiration of subalpine forests. I. Model development. *Can. J. For. Res.* 14, 18-226.

Kimball, B. A. 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. *Agron. J.* 75, 779-788.

Kramer, P. J. 1981. Carbon dioxide concentration, photosynthesis, and dry matter production. *BioScience* 31, 29-35.

Kramer, P. J. 1983. *Water Relations of Plants.* Academic Press, Inc., New York.

Kramer, P. J., and T. T. Kozlowski. 1979. *Physiology of Woody Plants.* Academic Press, Inc., New York.

Kriedemann, P. E., R. J. Sward, and W. J. S. Downton. 1976. Vine response to carbon dioxide enrichment during heat therapy. *Aust. J. Plant Physiol.* 3, 605-609.

LaMarche, V. C., Jr., D. A. Graybill, H. C. Fritts, and M. H. Rose. 1984. Increasing atmospheric carbon dioxide: tree ring evidence for growth enhancement in natural vegetation. *Science* 225, 1019-1021.

Lincoln, D. E., N. Sionit, and B. R. Strain. 1984. Growth and feeding responses of *Pseudoplusia includens* (Lepidoptera: Noctoidae) to host plants growth in controlled carbon dioxide atmospheres. *J. Environ. Entomol.* 13, 1527-1530.

Miller, E. C. 1938. *Tree Physiology, 2nd ed.*, p. 458-459. McGraw-

Hill, New York.

Nobel, P. S. 1980. Leaf anatomy and water use efficiency, p. 43-55. *In* N. C. Turner and P. J. Kramer (ed.), *Adaptation of Plants to Water and High Temperature Stress.* Wiley, New York.

Osmond, C. B., O. Bjorkman, and D. J. Anderson. 1980. Physiological processes in plant ecology. Ecological Studies 36. Springer-Verlag, New York.

Patterson, D. T. and E. P. Flint. 1982. Interacting effects of CO_2 and nutrient concentration on soybean (*Glycine max*), sicklepod (*Cassia obtusifolia*), and showy crotolaria (*Crotolaria spectabilis*). *Weed Sci.* 30, 389-394.

Pearcy, R. W., and O. Bjorkman. 1983. Physiological effects, p. 83, 84. *In* E.R. Lemon, (ed.), *CO_2 and Plants--the Response of Plants to Rising Levels of Atmospheric Carbon Dioxide.* Westview Press, Boulder, Colo.

Regehr, D. L., F. A. Bazzaz, and W. R. Boggess. 1975. Photosynthesis, transpiration and leaf conductance of *Populus deltoides* in relation to flooding and drought. *Photosynthetica* 9, 52-59.

Rogers, H. H., G. E. Bingham, J. D. Cure, J. M. Smith, and K. A. Surano. 1983. Responses of selected plant species to elevated carbon dioxide in the field. *J. Environ. Qual.* 12, 569-574.

Sharp, R. E., and W. J. Davies. 1979. Solute regulation and growth by roots and shoots of water-stressed maize plants. *Planta* 147, 43-49.

Sinclair, T. R., C. B. Tanner, and J. M. Bennett. 1984. Water use efficiency in crop production. *BioScience* 34, 36-40.

Sionit, N. 1983. Response of soybean to two levels of mineral nutrition in CO_2-enriched atmosphere. *Crop Sci.* 23, 329-333.

Sionit, N., H. Hellmers, and B. R. Strain. 1982. Interaction of atmospheric CO_2 enrichment and irradiance on plant growth. *Agron. J.* 74, 721-725

Sionit, N., and P. J. Kramer. 1984. Woody plants reactions to carbon dioxide enrichment. *In* H. Z. Enoch and B. A. Kimball (ed.), *Carbon Dioxide Enrichment of Greenhouse Crops.* CRC Press, Boca Raton, Fl. (in press).

Sionit, N., D. A. Mortensen, B. R. Strain, and H. Hellmers. 1981a. Growth response of wheat to CO_2 enrichment and different levels of mineral nutrition. *Agron. J.* 73, 1023-1027.

Sionit, N., B. R. Strain, and H. A. Beckford. 1981b. Environmental controls on the growth and yield of okra. I. Effects of temperature and of CO_2 enrichment at cool temperature. *Crop Sci.* 21, 885-888.

Sionit, N., B. R. Strain, H. Hellmers, and P. J. Kramer. 1981c. Effects of atmospheric CO_2 concentration and water stress on water relations of wheat. *Bot. Gaz.* 142, 191-196.

Sionit, N., B. R. Strain, H. Hellmers, G. H. Riechers, and C. H. Jaeger. 1985. Long term atmospheric CO_2 enrichment affects the growth and development of *Liquidambar styraciflua* L. and *Pinus taeda* L. seedlings. *Can. J. For. Res.* (in press).

Strain, B. R., and F. A. Bazzaz. 1983. Terrestrial plant communities, p. 179, 193. *In* E. R. Lemon (ed.) *CO_2 and Plants--The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide*. Westview Press, Boulder, Colo.

Tolley, L. C. 1982. The effects of atmospheric carbon dioxide enrichment, irradiance and water stress on seedling growth and physiology of *Liquidambar styraciflua* and *Pinus taeda*. Ph.D. dissertation. Duke University, Durham, N.C.

Tolley, L. C. and B. R. Strain. 1984a. Effects of CO_2 enrichment on growth of *Liquidambar styraciflua* and *Pinus taeda* seedlings under different irradiance levels. *Can. J. For. Res.* 14, 343-350.

Tolley, L. C., and B. R: Strain. 1984b. Effects of atmospheric CO_2 enrichment and water stress on growth of *Liquidambar styraciflua* L. and *Pinus taeda* L. seedlings. *Can. J. Bot.* (in press).

Waggoner, P. E. 1984. Agriculture and carbon dioxide. *Am. Sci.* 72, 179-184.

Wong, S. C. 1979. Elevated atmospheric partial pressure of CO_2 and plant growth. I. Interactions of nitrogen nutrition and photosynthetic capacity in C_3 and C_4 plants. *Oecologia* 44, 68-74.

Wulff, R. D., and B. R. Strain. 1982. Effects of CO_2 enrichment on growth and photosynthesis in *Desmodium paniculatum*. *Can. J. Bot.* 60, 1084-1091.

Zangerl, A. R. and F. A. Bazzaz. 1984. The response of plants to elevated CO_2. II. Competitive interactions among annual plants under varying light and nutrients. *Oecologia* (in press).

WORLD RESOURCES INSTITUTE
A CENTER FOR POLICY RESEARCH

1735 New York Avenue, N.W., Washington, D.C. 20006, Telephone 202-638-6300

TESTIMONY OF WILLIAM R. MOOMAW
BEFORE THE SENATE AGRICULTURE COMMITTEE
DECEMBER 1, 1988

Mr. Chairman, I am William R. Moomaw, Director of the Climate, Energy and Pollution Program of the World Resources Institute (WRI). I appreciate the opportunity to appear before you today on the subject of forestry policy and global warming.

As you are aware, the public concern over global warming has surged recently, partially in response to the heat and drought of this past summer. Scientific debate on the likelihood and magnitude of human-induced global warming, however, has been underway for almost a century. Notwithstanding remaining uncertainties about the timing and severity of global warming, it is now generally accepted within the scientific community that fossil fuel combustion, as well as other industrial and agricultural activities of human societies, have already committed the planet to significant warming, and that additional warming in likely far into the next century and beyond.

The basic mechanism for global warming was first proposed in 1827 by the French mathematician and physicist Jean Fourier. He suggested that the earth is as warm as it is because the atmosphere has special greenhouse-like properties. These properties permit solar energy to enter and strike the earth, but then absorb a portion of that energy as it attempts to radiate back into space. This trapped energy keeps the planet warmer than it would be in the absence of the atmosphere. In 1896, the great Swedish chemist Svente Arrhenius not only demonstrated that it was the traces of water vapor and carbon dioxide in the atmosphere that trapped the infrared energy, but also calculated the amount of additional warming that could be expected if the combustion of fossil fuels doubled the atmospheric carbon dioxide concentrations. His estimate of a 10 degrees F warming is not much higher than the 3 to 8 degrees F increase that current models project for a doubling of atmospheric CO_2.

The pace and eventual magnitude of global warming depend on variables as disparate as global population growth, energy supply mix, changes in ocean currents, deforestation rates, chlorofluorocarbon (CFC) consumption, and positive and negative climatic feedbacks. One potential feedback is the effect of global warming on clouds. Because of the complexity of the feedback mechanism, however, we remain unsure as to the magnitude, type, and distribution of any increase in cloudiness, and can therefore not be sure whether increased cloudiness would cool or further warm the planet. Other feedbacks are more straightforward, such as the likelihood that global warming will increase the rate of decay of organic matter, potentially adding significantly to the release of CO_2 and methane into the atmosphere.

Our current understanding of the interplay between atmospheric concentrations of greenhouse gases and global temperatures suggests that under a "high emissions" scenario we could commit ourselves to a 3 to 8 degrees F rise in average global temperatures by as early as 2015, and even under a "base case" scenario such a commitment is projected to occur by 2030. Indeed, current data suggests that the planet has already warmed by 1 degrees F during the past century, consistent with projections of the impacts of past additions of greenhouse gasses to the atmosphere, and that we may already be committed to an additional average temperature rise of 2 to 4 degrees F.

Human activities in a wide variety of areas are contributing to changing the planet's atmosphere and overall heat balance. Any significant temperature changes which result will have profound consequences for all sectors of human activity. Attempting to slow or adapt to global warming thus suggests a complex mosaic of anticipatory and adaptive policy strategies. Today, I would like to address just one part of the global warming puzzle, namely forestry and forestry policy. Forests are very vulnerable to the impacts of global warming, and the timespans required for forest regeneration suggest that the consequences of global warming will take a long time to reverse, if that is even possible. A variety of specific approaches can be envisioned which could help protect forests from some of the impacts of global warming, and which could use forests to reduce or mitigate the effects of domestic and international CO_2 emissions, thereby slowing global warming. Overall, domestic forestry initiatives may well have the ability to offset or reduce U.S. CO_2 emissions by more than 15 percent, equivalent to the annual emission of more than 200 million tons of carbon. Internationally, much more could be accomplished.

My testimony will include a review of the possible implications of global warming for the health, distribution, and productivity of our forests, suggestions for the types of adaptive strategies we would be well served to consider as part of our ongoing forest management activities, and thoughts about the specific role forests and forestry policy can play in moderating the pace and severity of global warming.

FORESTS IN THE GLOBAL CARBON CYCLE

In considering the general role of forests in affecting or responding to climatic change, it is helpful to review their role in the global carbon cycle. The carbon cycle is important because it determines how much carbon, in the form of carbon dioxide (CO_2), is in the atmosphere at any one time. It is perturbations to the carbon cycle, primarily the annual release of six billion tons of carbon through the combustion of fossil fuels, as well as the annual release of over a billion tons of carbon through deforestation, that are expected to be responsible for 50 percent of the global warming seen in the next several decades. As a result of these perturbations, the concentration of CO_2 in the atmosphere has increased from a preindustrial level of about 280 parts per million (ppm) to today's levels of 350 ppm.

Figure 1 illustrates the global carbon cycle. The atmosphere now contains some 750 billion tons of carbon, which is already 150 billion tons more than it contained prior to the commencement of large-scale fossil fuel combustion. The surface ocean and biota contain some 725 billion tons, while terrestrial life accounts for some 560 billion tons. Another 1,460 billion tons is sequestered in ground litter and soils. The vast majority of global carbon is sequestered in the deep ocean (some 38,000 billion tons) and in fossil fuels (up to 7,000 billion tons). It is believed that the deep ocean carbon is stable over long periods of time. Similarly, fossil fuels would be a stable carbon reservoir in the absence of human intervention. Human activities, however, open a conduit for carbon sequestered in fossil fuels and terrestrial tropical forests to escape to the atmosphere.

The injection into the carbon cycle of large quantities of carbon from fossil fuel combustion, or the reallocation of large quantities of carbon between terrestrial biota and the atmosphere through the deforestation of 25 million acres per year, raises the size of the atmospheric reservoir of carbon in the form of CO_2. This in turn contributes to global warming. There are two basic ways that forestry policies can help to slow global warming. The first is to slow and eventually reverse net deforestation, now a particular problem in the tropics, which allows the leakage of sequestered carbon into the atmosphere. This approach can be augmented by increasing the net size of the terrestrial carbon sink by expanding the standing crop of trees, as well as by building up the carbon content of forest, grassland, and agricultural soils. Secondly, forestry productivity rates can be increased so that forests absorb a higher percentage of the annual carbon dioxide emissions from human activities.

IMPACTS OF GLOBAL WARMING ON U.S. FORESTS

While average global temperatures may rise by between 3 and 8 degrees F during the next century, temperature increases will be proportionately greater at northern latitudes. There is no doubt that the expected degree of warming would have dramatic impacts on forests around the world.

First, as shown in Figures 2 and 3 by changes in lifezone distributions, the ranges of most forest species would move up in elevation and north in latitude. Because a 1 degree F temperature change is roughly equivalent to a latitudinal shift of 40 miles, and because particularly dramatic temperature changes will occur in high latitudes, species ranges could shift by 200 to 500 miles. Although all species of fauna and flora are constantly shifting their ranges in response to slowly changing climate, as shown in Figure 4, the severity and speed of likely future climatic changes will be an order of magnitude beyond those experienced by species in the past. This will pose severe problems for species adaptation. Tree species will be unable to extend their geographic range nearly as quickly as climatic and other environmental conditions would dictate, or to adapt readily to the specific soil and hydrological circumstances found there. There will therefore be a substantial time lag in the colonization of new areas by forests. In attempting to migrate northward, species will be severely constrained by barriers not faced in previous migrations, e.g. metropolitan and agricultural development. Many species of plants and animals will no doubt become extinct.

Second, to whatever extent tree species successfully track changing climatic ranges, the species composition of the forest communities we are now familiar with will be quite disrupted. It will be individual species rather than forest communities that adapt and migrate as best they can. Major changes will occur to ecosystems, and the relative composition of economically valuable vs. less valuable tree species is likely to change considerably. Figure 5, taken from the new EPA effects report, shows the projected shift in range for sugar maple and hemlock which would be projected to accompany a 3 to 8 degrees F temperature increase.

Third, changing species ranges will not neatly accommodate current patterns of resource ownership. Those plant and animal communities around which our national forests, national parks, and wildlife refuges are built will suddenly be forced to move north. Will we attempt to establish a whole new set of mobile species refuges and national forests to track their migration? And if global warming is proceeding rapidly, would such a strategy make sense even if it were physically possible? In the absence of such efforts, what will prevent the extinction of many of these species?

Fourth, already established forests in the southern parts of species' current ranges will be severely stressed as the climatic conditions favorable to their continued growth and regeneration move northward. There is some argument that higher atmospheric concentrations of CO_2 will have a fertilizing effect on forests, and that this may offset some of the difficulties imposed by global warming. For many forests, however, nutrient and water availability, rather than CO_2 concentrations, are likely to be the variables currently limiting forest growth. These variables, along with new ones such as possible increases in cloud cover, would offset much if not all of the CO_2 fertilization effect. In addition, water availability and soil moisture will change, fire regimes will become more intense, and seedlings may be unable to regenerate. Insect pests and other pathogens undertaking more rapid migrations of their own from points south will add to the problems of these forests. These stresses are likely to be reflected in reduced general forest health, altered growth rates, lower quality of lumber, and deteriorating wildlife habitats.

ADAPTING FOREST MANAGEMENT STRATEGIES TO GLOBAL WARMING

As just discussed, any significant amount of global warming will badly stress existing forests, and do serious damage to spatially defined structures such as the National Forest system. The best strategy we can pursue to protect our forests and the timber industry that is dependent on them is to slow as much as possible the rate of global warming, thereby giving natural adaptation more time to work. Ultimately, we must strive to halt human-induced global warming altogether. Nevertheless, and even if one accepts that significant consequences will accompany global warming, it could be argued that over the long term we will adjust to whatever changes in forest distribution and composition occur. But given the ecological and economic importance of forests both domestically and internationally, this is a high-risk approach. Instead, we should undertake to protect our forests as best we can from the impacts of global warming. In addition, the prognosis for U.S. forests may be improved by helping them to adapt to an unparalleled rate of climate change.

First, we should act to minimize other human-imposed stresses on the forests. The World Resources Institute recently published a study of the impacts of air pollution on agricultural and forest production. In Ill Winds: Airborne Pollution's Toll on Trees and Crops, WRI researchers conclude that ozone, acid rain, and other pollutants are having significant effects on the growth rates and health of standing forests in the Northeast. In what may well be a related issue, the Forest Service is attempting to determine the causes of rising mortality and decreased growth on commercial timberlands in the southeastern U.S. The fact is that pollutants emitted by the combustion of fossil fuels for electricity production and transportation are seriously stressing domestic forests. The results of this stress will become increasingly evident as global warming adds to the strains facing forests, and as their abilities to grow and adapt to changing conditions decrease as a result.

Beyond trying to control air pollution, forestry policy should address all sources of stress to standing forests. Current harvesting and management practices should be reevaluated in light of global warming to determine whether they unnecessarily stress the forests being managed. The implications of global warming for drought, fire ecology, pest infestation, and future species mix also need to be considered during such a reevaluation.

Second, we should be undertaking considerably more research to determine how to help forests adapt to changing climatic conditions. This includes not only research into how to artificially accelerate a species' ability to migrate with changing climatic conditions, but how existing forest growth and stability can be encouraged in the face of changing environmental conditions. For example, should routine replanting of harvested areas take the place of increasingly uncertain natural regeneration? Should new species be emphasized during replanting programs, species that are better adapted to the conditions which may prevail 50 years from now in a particular area? These are just some of the questions foresters are beginning to raise as they consider the implications of global warming.

USING FORESTRY POLICY TO SLOW OR MITIGATE GLOBAL WARMING

Trees are approximately 50 percent carbon by dry weight. As stated previously, deforestation and the subsequent release of carbon to the atmosphere can aggravate global warming. Conversely, adding significantly to the standing stock of trees can remove large quantities of CO_2 from the air, thus helping to slow and mitigate the buildup of atmospheric CO_2.

More and more attention is now being given to the prospects for fighting global warming through aggressively increasing the amount of carbon stored in world forests. Unfortunately, the destructive impacts global warming is likely to have on domestic and world forests makes using forests to combat the rate or severity of global warming a somewhat tenuous proposition. It may be more than we can accomplish to maintain a forest system similar to the status quo in terms of carbon sequestration. Nevertheless, the potential usefulness of forests in combatting global warming is a policy option that we can begin to implement now, and one that is certain to slow the growth of the major greenhouse gas, carbon dioxide.

Forestry as a Part of the Solution

Several estimates exist with respect to how many acres of trees would have to be planted to solve, albeit only temporarily, the problem of global warming by absorbing in new biomass enough carbon dioxide to offset the emissions of fossil fuel combustion. These estimates range from 1.2 billion acres to 3 billion acres, compared to a total U.S. surface area of some 2.2 billion acres. While it is conceivable that in the throes of a global crisis induced by global warming such an ambitious program might be undertaken, this approach cannot be expected to "solve" global warming anytime soon, and we should not rely on it.

Nevertheless, it does appear that forestry can play a significant role in absorbing a significant portion of total CO_2 emissions. As Figure 6 clearly shows, the electric utility and transportation sectors of the U.S. have increased their CO_2 emissions since 1973, whereas the industrial, commercial, and residential sectors have example, the North American Electric Reliability Council estimated in 1987 that over 25,000 megawatts (MW) of electric power generating capacity will be added in the U.S. through 1996, emitting over 45 million tons of carbon annually. We estimate that to absorb this amount of carbon would probably require the planting of approximately 30 million acres of trees in the U.S., a surface area equivalent to the state of Mississippi. Perhaps the builders of new facilities such as powerplants should be required to offset a new project's CO_2 emissions, just as they already have to do under some circumstances for a variety of other air pollutants. The concept of offsets might also be taken beyond stationary sources to include incremental additions to U.S. automobile and truck fleets, the CO_2 emissions of which are likely to grow by some ten million tons annually (2.7 million tons carbon). To absorb the additions from the transportation fleet would require the planting of one to two million acres of new forest every year. While superficially a modest step towards addressing global warming, even offsetting incremental additions to current levels of CO_2 emissions from the power generation and transportation sectors could play a significant role in slowing global warming.

It must be accepted from the outset, however, that the ultimate contribution of forestry can only be to facilitate a transition from our reliance on fossil fuels to non-CO_2 releasing fuel sources over the next 50 to 75 years. There is no conceivable way that forestry could indefinitely compensate for the quantities of carbon that would be emitted to the atmosphere through an indefinite reliance on fossil fuels. Even if some enormous surface area of land could be planted in coming years, the withdrawal of large quantities of CO_2 from the air would continue only as long as the trees were rapidly growing.

In addition, the relatively small part that U.S. forests play in the global carbon cycle suggests that fully effective forest-based mitigation strategies will have to be international in scope. U.S. National Forests appear to be a repository for some 3 billion tons of carbon. This compares to some 12 billion tons for all U.S. timberlands, and less than 20 billion tons for U.S. forests as a whole.[1] This compares to estimates of the carbon content of tropical forests of from 200 to 500 billion tons.

Policies to Encourage Carbon Storage on Federal Lands

The actual magnitude of the role domestic and global forestry can play in offsetting some proportion of CO_2 emissions is still uncertain. It is obvious, however, that forest policy can certainly affect the volume of carbon sequestered in standing stock, as well as the growth rates of the nation's forests. Some aspects of forest management practices domestically and around the world require a fundamental rethinking in light of the threats posed by global warming. At the domestic level, the following types of measures would contribute to maximizing the role of our forests in combatting global warming:

- Increasing tree growth rates on national forest lands managed for timber should be encouraged through more aggressive management and by accelerating the

---

[1] Forest is classified as timberland only when it is capable of producing at least 20 cubic feet per acre of industrial wood annually, and when it has not been reserved from timber harvest. Only two-thirds of the nation's forests are classified as timberlands.

- Increasing tree growth rates on national forest lands managed for timber should be encouraged through more aggressive management and by accelerating the replanting of harvested areas. Waiting for natural regeneration can postpone significant carbon reaccumulation by several years, and it can facilitate the release of soil carbon. While there has been reported progress in reforesting a long-standing backlog of U.S. Forest Service harvested areas, much of this progress may be illusory. A 1985 report to the Committee on Appropriations by its Surveys and Investigations Staff revealed that the Forest Service sometimes claims treatment of backlog acres even when no tree planting is planned, before planned planting has occurred, or when only a part of an area is in fact treated. The report concluded that large portions of the backlog acres were removed from the rolls not by reforestation, but by administrative fiat reclassifying the land out of the timberland system. A more recent report by the Congressional Research Service comes to the same conclusion. Yet if the land was not appropriate for reforestation, why was it cut in the first place? Such land may best be utilized as a carbon sink rather than being cut at all. I believe the Forest Service needs additional funding to actually keep up with the reforestation needs of harvested timberlands. I would encourage the Committee to authorize the additional funds needed for reforestation activities by the Forest Service, with an eye toward improving the role of these lands as carbon stores.

- I suggest that carbon fixation and storage to slow the building of atmospheric carbon dioxide be added to the multiple use management criteria for national forests. Taking into account the carbon storage role of these forests would have some significant management implications. In timberlands on the Pacific Coast, average standing carbon stock is some 42 tons per acre, yet average growth is only about 1 ton per acre. Forests with naturally low growth rates, such as Tongass National Forest, are even more disparate in standing stock vs annual growth, and may best serve carbon storage purposes by being left standing as carbon reservoirs. It would be very difficult to make up through new growth the large amount of carbon released from the trees and the soil during the harvesting of such a forest. Conversely, the productivity of other timberlands should be maximized through rapid rotations to increase the rate of new carbon fixation, particularly if the forest's products serve to advance long-term carbon storage goals, e.g. through the production of construction materials. It will require considerable site-specific research to determine how particular forest stands should be managed in the most appropriate way to meet a stated policy goal of carbon fixation and storage.

- The potential for reforestation or afforestation on other public lands should be evaluated, and planting programs undertaken where appropriate. These lands might include active and closed military bases, Bureau of Land Management lands, Indian reservation lands, as well as state and local parks and forests. Although it is very difficult to determine how much potential for afforestation exists on these lands, it must amount to several tens of millions of acres.

- Most of the steps suggested above will require research into how best to balance the sometimes competing management criteria of timber production, carbon fixation, habitat development, and recreational access. Beyond this research, improvements continue to be needed in the Forest Service's data base of our national forest resources. The Service needs funds to improve its information gathering and analysis capabilities with respect to forest growth and regeneration status.

- Additional research and development is required to develop faster growing trees that can adapt to changing environmental conditions. Unfortunately, expenditures for Forest Service research and development fell by 25 percent in real terms between 1977 and 1986, and have only marginally recovered since then. I urge that the research budget be returned to at least its former level, and preferably increased.

- Subsidies which encourage the uneconomic cutting of forests should be ended. Cutting down trees when it makes no economic sense is even less prudent when done in the face of global warming. The evidence suggests that heavily subsidized, below-cost timber sales in the Tongass National forest and many other national forests cost U.S. taxpayers more than $85 million dollars per year, despite the fact that at least some of the areas are simply unsuitable for timber production and should be managed for other purposes. According to the Congressional Research Service, more than 95 percent of the timber sale receipts on 8 national forests in 1987 were accounted for by deposits to the Knutson-Vandenberg (K-V) accounts to cover replanting, and by credits for road-building. K-V deposits and road credits exceeded 75 percent of the timber sale receipts in 35 national forests during the same year. Despite Congressional attempts to reduce indirect subsidies such as road building, they continue to be a major factor in promoting uneconomic harvesting activity. If the total costs of administering timber sales were to be included, many of these timber sales are properly classified as net losses to the U.S. taxpayer. In light of the valuable role of standing forests for carbon storage, counterproductive policies such as those cited by the Congressional Research Service, and discussed extensively in earlier governmental and non-governmental studies, should be discouraged. Aside from the economic issue, it is very difficult for the U.S. to argue that countries such as Brazil should be ending the subsidies which are contributing to the deforestation of the Amazon rain forest when we continue to subsidize the uneconomic harvesting of our own forests.

The problem of finding funds to support the research and reforestation program costs is a severe one during times of tight budgetary constraints. I would propose that the funding for these new programs come from the savings achieved from the eliminated subsidies, and possibly from revenues collected through a charge on the emissions of carbon dioxide. Alternatively, a specific offset program could be instituted through which a prospective major emitter of CO_2 would be required to fund forestry or other activities which would in effect offset the quantity of carbon expected to be emitted.

Policies to Encourage Carbon Storage on Non-Federal Lands

Because federally owned timberlands are less than 20 percent of total U.S. timberlands, strategies intended to increase carbon fixation through forestry must involve private lands as well. This is particularly the case because it is on private timberlands that the greatest increases in forest productivity are achievable according to the Forest Service. A number of approaches are possible:

- It is already Congressional policy that some proportion of the lands set aside as part of the Conservation Reserve Program (CRP) should be forested. In light of the seriousness of the problem of global warming, perhaps the target for forestation on these lands should be raised considerably from the current 12 percent, and the contract terms of the CRP should be modified so as to provide additional incentives for such forestation. Dr. Daniel Dudek of the Environmental Defense Fund has already detailed a proposal through which the CO_2 emissions of the previously discussed 25,000 MO of powerplants to be constructed by 1996 could be cost-effectively offset. Dudek proposes that 10 million acres of new forests on CRP lands could annually absorb over 45 million tons of carbon, thus offsetting the powerplants' emissions. In addition to forest establishment costs of 1.3 to 1.6 billion dollars, Dudek estimates that the annual costs of the program would amount to 0.33 to 0.67 cents per kilowatt hour (kWh). Our own analysis assumes more modest growth rates for the trees being planted,[2] and suggests that up to 30 million acres of new conventional forest might in fact be required. Because of the significant potential for carbon fixation, however, and because of the ancillary benefits involved in reforesting CRP lands, we see the use of CRP lands for carbon storage as an excellent idea that should be further investigated and encouraged.

- Increasing timber growth on private timberlands needs to be encouraged. Accelerating the regeneration or replanting of harvested lands has significant potential, as does more intensive management. The Forest Service estimates that growth on private non-industry lands could be cost-effectively increased by almost four billion cubic feet per year (about 28 million tons of carbon), an increase of some 30 percent over current growth rates. This increased growth could mitigate over 2 percent of net U.S. carbon emissions, or over 50 percent of the emissions from new powerplants to be built in the coming decade. In encouraging such growth, however, competing interests in the form of the economic value of forest products, biological diversity, and other values must always be considered.

- The potential for forest-derived biofuels should be better assessed, and fostered if found worthwhile. Foresters at the Oak Ridge National Laboratory estimate that in addition to the three percent of total U.S. energy consumption currently provided by wood fuels, production of liquid fuels such as methanol from fast growing tree plantations could on a net basis add another 4 quads to

---

[2] Many variables contribute to the growth and consequent carbon fixation rates achieved in forestry projects. In conventional forestry trees are planted and left to grow for an extended period of time, generally without extensive additional inputs. In intensive fast-rotation forestry trees are treated as a 5 to 8 year crop, and are intensively managed to maximize growth potential. The carbon fixation rates achievable under these two extremes no doubt differ dramatically. It is uncertainty over the type of forestry to be employed and the carbon fixation that is achievable that underlies the wide range of estimates of land area requirements. This uncertainty points up the need for additional forestry research and development activities.

U.S. renewable energy resources, thus reducing U.S. fossil fuel consumption and CO_2 production by some 6 percent. One must be careful, however, in assessing the net energy balance of such biofuel projects, and especially the fossil fuel inputs, to insure that there is a real reduction in CO_2 emissions. Some biofuel projects in the past have relied so heavily on fossil fuel inputs in the form of fertilizers and other aids that many of the energy benefits claimed for the resulting biofuels were not met on a net basis.

- Farming and forestry practices which encourage the buildup of large quantities of carbon in the soil should be investigated and encouraged. Globally, two to three times as much carbon is stored in soils as is found in surface biomass. In light of the many depleted soils domestically and around the world, and the rapid rate at which additional soils are being depleted, it is likely that a huge amount of carbon could be sequestered in this manner. Unfortunately, many prevalent agricultural and forestry practices result in the release of carbon from the soil to the atmosphere, rather than its sequestering. Delaying reforestation of harvested forests, for example, facilitates carbon release through wind and water erosion of the soil and subsequent oxidation.

- A variety of "urban forestry" projects are currently underway, and should be encouraged. Dr. Arthur Rosenfeld of the University of California at Berkeley has shown that urban tree planting can help cool down urban areas and significantly reduce air conditioning bills. In a similar vein, the American Forestry Association (AFA) recently kicked off a campaign which it hopes will result in the planting of 100 million trees. Urban forestry could conceivably reduce U.S. energy consumption by 0.6 percent by reducing cooling requirements, thereby lowering carbon emissions by some 10 million tons annually. Interestingly, the direct carbon fixation benefits of planting the trees is very modest. Even complete AFA success with its goal of planting 100 million trees around the country would probably drain less than one million tons of carbon out of the atmosphere each year.

Each of the individual forestry-based approaches discussed above appear quite modest in their ability to offset domestic CO_2 emissions. Overall, however, these programs could reduce or offset domestic CO_2 emissions by more than 15 percent, or more than 200 million tons annually. These programs must be encouraged as a few of the many incremental steps that will be needed to successfully slow the pace of global warming. They are also very valuable as a means through which to raise public awareness around the country.

Policies to Encourage Carbon Storage Internationally

As mentioned previously, tropical forests are much larger carbon sinks than domestic or even temperate forests generally. In addition, they help stabilize global and regional climates, they shelter most of the world's genetic resources, and they represent valuable assets for economic development. Unfortunately, tropical forests are being felled at a rate of some 25 million acres per year, the equivalent of losing 25 percent of the U.S. National Forest system annually. The U.S. should help save tropical forests for many reasons including carbon storage, and there are a number of actions the U.S. should take to contribute importantly to addressing the tropical deforestation crisis:

- The CO_2 emissions of domestic powerplants and other facilities could be mitigated through forestry projects in other countries. Because of the global nature of the carbon cycle, planting trees abroad can be just as effective against global warming caused by U.S. CO_2 emissions as planting trees domestically. This is the principle behind the recently announced initiative by Applied Energy Services (AES), a domestic power company, and World Resources Institute to develop and fund a forestry project in Guatemala. This project is intended to have the effect of offsetting the carbon emissions of a soon to be constructed AES power plant which will emit some 15 million tons of carbon over its 40 year life. The forestry project, administered by the relief agency CARE, is intended to both fix and prevent the release of a total of more than 15 million tons of carbon over the same period. While carbon fixation forestry within the U.S. may be more reliable than foreign projects due to the population and other pressures existing in countries like Guatemala, the costs of such projects are much lower abroad, and they carry with them many ancillary social and economic benefits.

- The U.S. should encourage the full funding and implementation of the Tropical Forestry Action Plan (TFAP), prepared under the joint sponsorship of the U.N. Food and Agriculture Organization, the World Bank, the U.N. Development Program, and World Resources Institute. The TFAP provides a global framework for stimulating action to reduce deforestation and promote the sustainable use of tropical forest resources. National action plans are being developed within the TFAP framework in more than 50 countries, with support and assistance from bilateral and multilateral development assistance agencies. USAID should play a leadership role in this process.

- Steps should be taken to ensure that U.S. development assistance through bilateral and multilateral channels not contribute to the problem of tropical deforestation. The U.S. should push for a swift end to development assistance projects and programs, both bilateral and multilateral, that directly or indirectly promote deforestation. Various development projects in the power generation, water resource management, transport, mining, and commercial agriculture sectors have had serious adverse impacts on tropical forest resources.

- Development assistance programs should emphasize the need for reform of current economic and other policies within developing countries that encourage deforestation, such as subsidies and other fiscal incentives for forest exploitation and development in forested areas. The multilateral lending agencies, particularly the World Bank, have begun to address broader policy issues affecting the forest sector in the formulation of policy-based forestry sector loans. The U.S. should encourage other assistance agencies, particularly the regional development banks, to undertake similar programs.

- The U.S. should work with other tropical timber producer and consumer countries to promote the goal that tropical hardwoods be imported only from areas where sustained yield management is practiced. The International Tropical Timber Organization could provide the framework for this cooperation and should have full U.S. support. This effort should be accompanied by increased assistance to tropical timber producing countries in the sustainable management of natural and plantation forests.

- The policy agenda adopted as part of any overall or broad-based Third World debt relief or restructuring should include specific measures to conserve tropical forests.

- Serious exploration should be given to the idea of an international convention to protect the world's remaining tropical forest areas. Such a convention could be the vehicle for bringing about a "global bargain" in which the national interests of the industrial countries in slowing global warming and protecting world biological resources, both promoted by halting deforestation, are reflected in relief and forgiveness of Third World external debt. A list of fifteen key tropical countries in Latin America, Asia and Africa contains virtually all of the major debtor countries as well as the countries experiencing extensive deforestation. A debt-for-nature bargain among these countries and the industrial countries would promote long-term national interests North and South. Such an agreement should also provide aid for more sustainable development projects such as renewable energy.

CONCLUSIONS

Forests are very vulnerable to the impacts of global warming, and the time-spans required for forest regeneration suggest that the consequences of global warming will take a long time to reverse. National forests are especially at risk because of their limited boundaries, and often lack contiguous open areas into which to move. Therefore, anticipatory strategies are particularly important. I strongly recommend that since significant global warming is highly likely during the next half century, the U.S. Forest Service should include global warming considerations into its forest management plans.

As part of such a strategy, the Committee may wish to consider adding carbon fixation as one of the multiple uses under which National Forests are managed. Such a step would have significant implications for current forest management practices, particularly with respect to the subsidized harvesting of timber that might more productively be left standing.

A variety of specific approaches can be envisioned which would use forests to reduce or mitigate the effects of domestic and international CO_2 emissions, thereby slowing global warming. One approach that has specific promise is the linking of specific CO_2 emitting projects in the U.S. to offsetting forestry projects around the world, as is being undertaken by Applied Energy Services with its sustainable development forestry project in Guatemala. Afforestation on federal lands and accelerated reforestation after harvesting could sequester 25 to 40 million additional tons of carbon annually, equivalent to more than 2 percent of U.S. carbon emissions. Private timberlands have the potential to fix another 28 million tons of carbon annually beyond what they are fixing now, thus offsetting another 2 percent of U.S. carbon emissions. Afforestation or reforestation of an additional 30 million acres of private land, including Conservation Reserve Program lands, could offset another 4 percent of U.S. emissions. Urban forestry might reduce carbon emissions by 1 percent. The exploitation of tree crops for biofuels production could reduce U.S. emissions of

CO_2 by a further 5 to 6 percent. Increasing the organic content of forest and agricultural soils could also offset a large but indeterminate quantity of carbon emissions. Overall, domestic forestry initiatives may well have the ability to offset or reduce U.S. CO_2 emissions by more than 15 percent, and certainly have the potential to offset most if not all of future increases in CO_2 emissions until we make the transition away from fossil fuels.

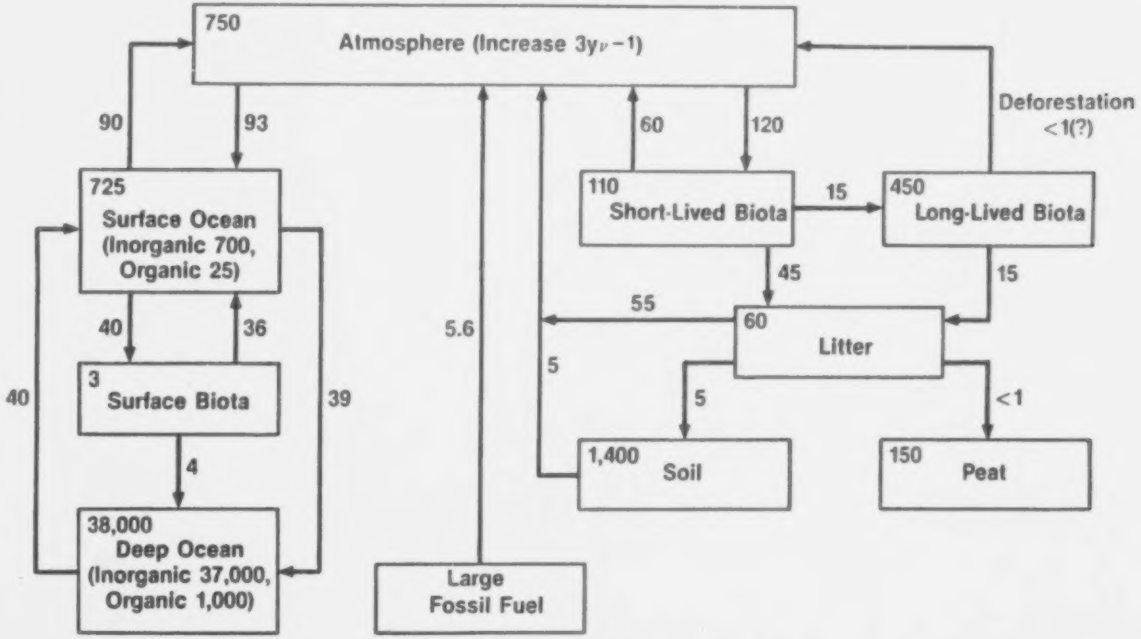
Internationally, even more could be accomplished. The types of programs outlined above for domestic application could be employed internationally to potentially reduce and offset worldwide CO_2 emissions by billions of tons. U.S. support for the Tropical Forestry Action Plan is needed, as is U.S. guidance to bilateral and multilateral aid agencies in the evaluation of projects which are likely to have significant forestry consequences.

Clearly, forestry cannot solve the entire problem of global warming, but it should play a crucial role along with energy efficiency and CFC phaseouts as we shift over the next 50 to 75 years to a non-CO_2 emitting energy base. To fail to utilize forests as part of the solution to slowing and moderating global warming will only assure that we will lose them as important economic, aesthetic, recreational and biodiversity resources.

(Figures 1 to 6 follow:)

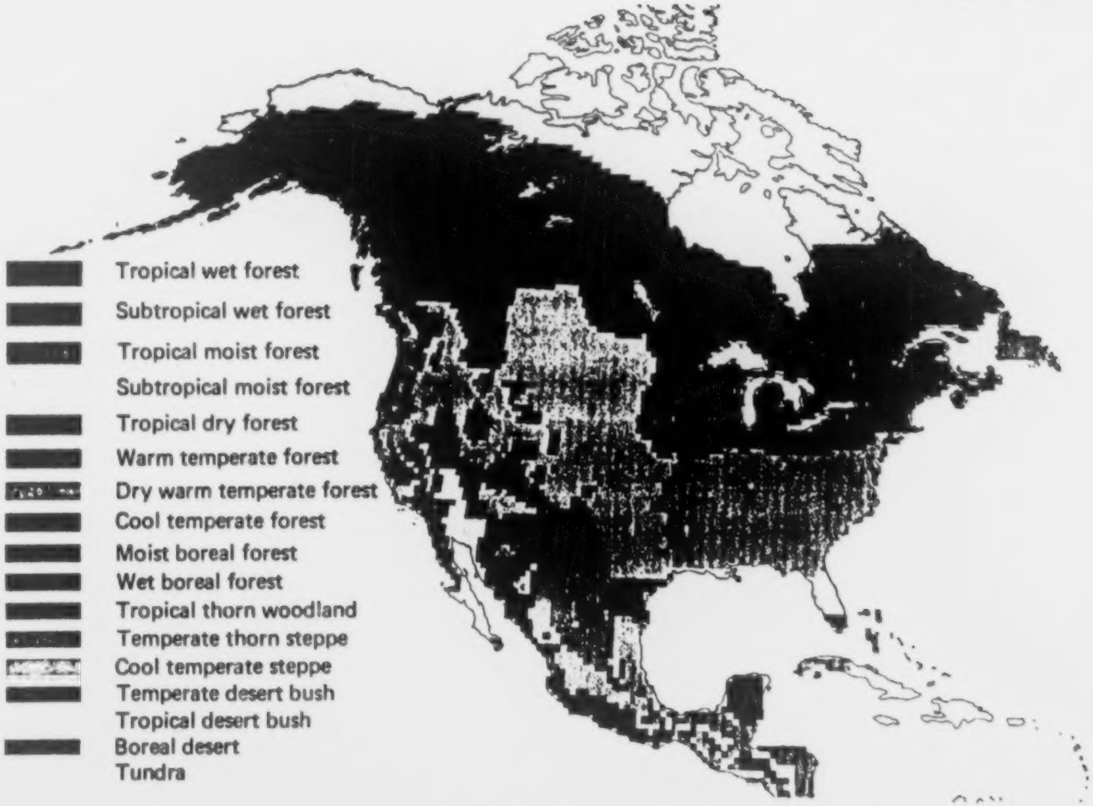
Figure 1

Carbon Cycle — 1987
(Units Gt)


750
Atmosphere (Increase 3yν−1)
90
93
60
120
Deforestation
<1(?)
725
Surface Ocean
(Inorganic 700,
Organic 25)
110
Short-Lived Biota
15
450
Long-Lived Biota
45
15
55
60
Litter
40
36
5.6
5
3
Surface Biota
40
39
5
<1
4
1,400
Soil
150
Peat
38,000
Deep Ocean
(Inorganic 37,000,
Organic 1,000)
Large
Fossil Fuel

Source: Gordon MacDonald
MITRE

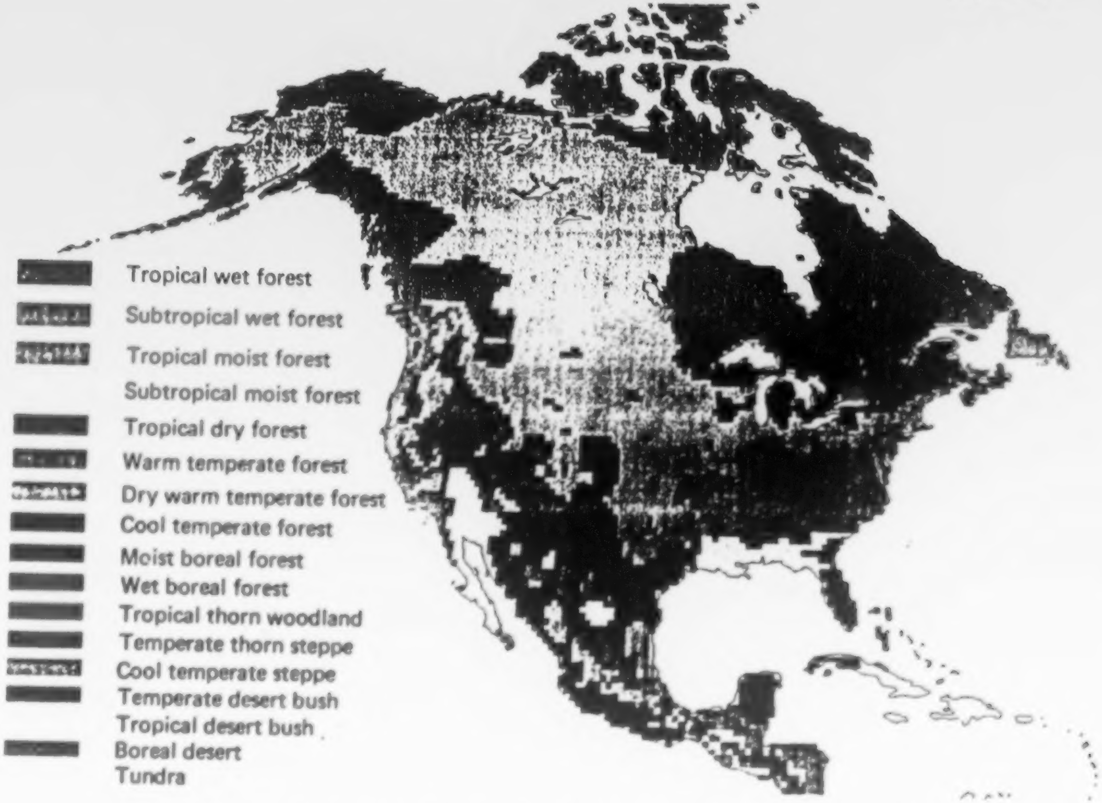
Figure 2


Tropical wet forest
Subtropical wet forest
Tropical moist forest
Subtropical moist forest
Tropical dry forest
Warm temperate forest
Dry warm temperate forest
Cool temperate forest
Moist boreal forest
Wet boreal forest
Tropical thorn woodland
Temperate thorn steppe
Cool temperate steppe
Temperate desert bush
Tropical desert bush
Boreal desert
Tundra

(*a*) Holdridge life-zone classification for present conditions of mean annual biotemperature and precipitation [58].

Source: Sustainable Development of the Biosphere
Clark, W.C. and Munn, R.C.
International Institute for Applied Analysis
page 396

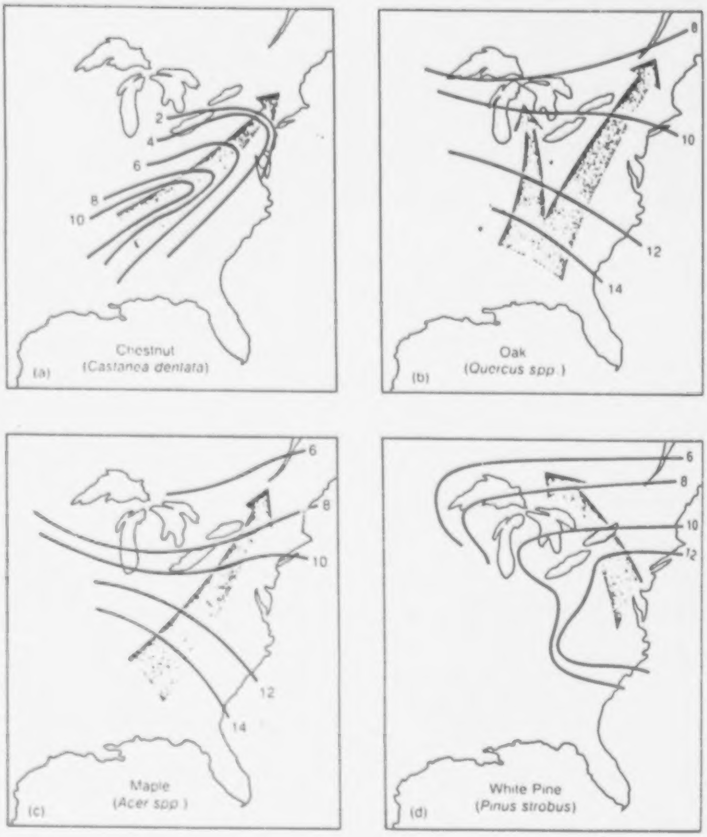
Figure 3


Tropical wet forest
Subtropical wet forest
Tropical moist forest
Subtropical moist forest
Tropical dry forest
Warm temperate forest
Dry warm temperate forest
Cool temperate forest
Moist boreal forest
Wet boreal forest
Tropical thorn woodland
Temperate thorn steppe
Cool temperate steppe
Temperate desert bush
Tropical desert bush
Boreal desert
Tundra

(*b*) Holdridge life-zone classification for doubling of CO_2 conditions of biotemperature (assuming unchanged precipitation) [58].

Source: Sustainable Development of the Biosphere
Clark, W.C. and Munn, R.E.
International Institute for Applied Analysis
page 397

Figure 4

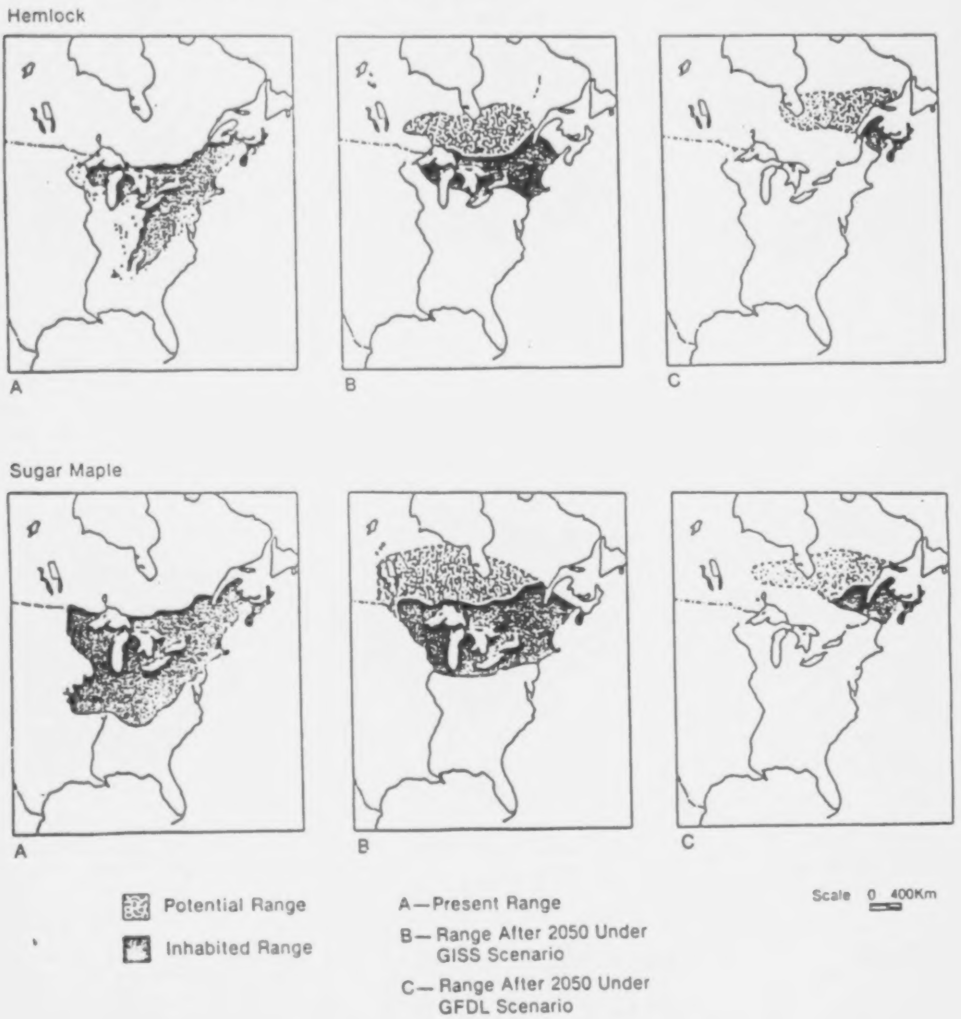


Changes in distribution of tree species during the last 10,000 years in North America. At the end of the last glacial period, as the climate warmed, tree species began to migrate northward. The history of their migration can be traced by studying pollen deposits in lakes. These graphs show the time (in thousands of years) that the pollen of chestnut (a), oak (b), maple (c), and white pine (d) first appeared at different areas of North America. From this information, one can reconstruct the general path of the migration (shown by the arrows). Chestnut, oak, and maple migrated from a refuge in the south central United States; white pine migrated from the southeast, from a refuge now offshore and under water. From a geological perspective, these species have been together in the mid-Atlantic states for a relatively short time. Chestnut reached the vicinity of what is now New York City about 2000 years ago, but oak arrived there 8000 years earlier. The forests first seen by the early European explorers (and thought to be relatively permanent associations of species) were ones that had changed in the preceding several thousand years. (From Davis, 1981.)

Source: Environmental Studies, The Earth as a Living Planet
Botkin, Daniel, B. and Keller, Edward A.
Merrill Publishing Company

Figure 5

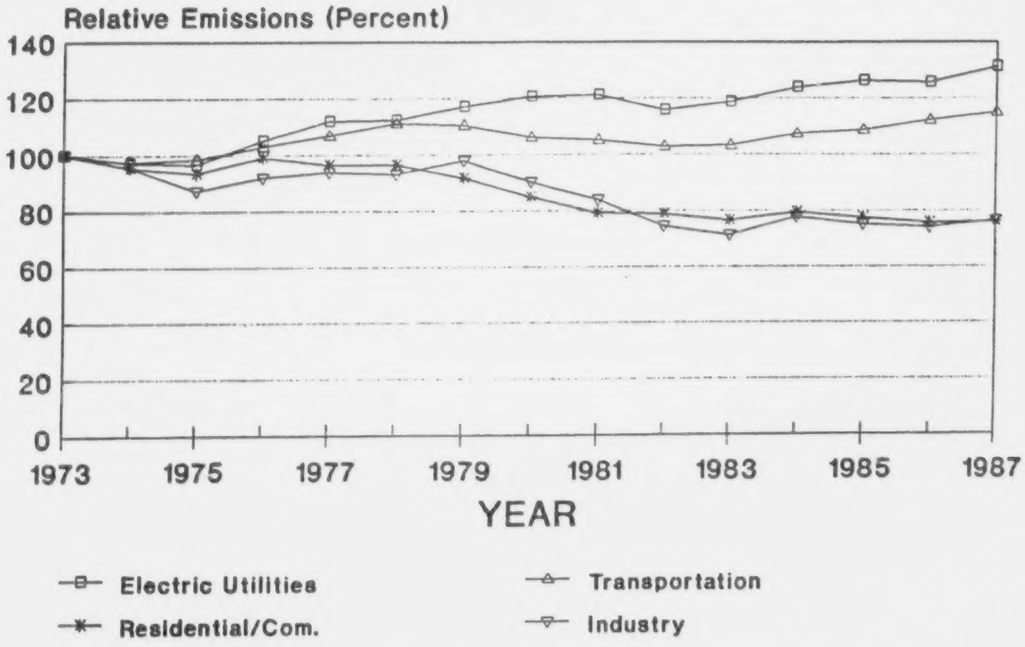
SHIFTS IN RANGE OF HEMLOCK AND SUGAR MAPLE UNDER ALTERNATIVE CLIMATE SCENARIOS


Hemlock
A
B
C
Sugar Maple
A
B
C
Potential Range
Inhabited Range
A—Present Range
B—Range After 2050 Under GISS Scenario
C—Range After 2050 Under GFDL Scenario
Scale 0 400Km

Source: Zabinski and Davis
From the Executive Summary draft report
Potential Effects of Global Climate Change on the United States
October, 1988

Figure 6

U.S. CARBON DIOXIDE EMISSION TRENDS
(1973 = 100%)



Source: World Resources Institute

**RESOURCES
FOR THE FUTURE**
1616 P STREET, N.W.
WASHINGTON, D.C. 20036

8

Climate and Forests

Roger A. Sedjo
Allen M. Solomon

There is general agreement that the observed rise in global carbon dioxide (CO_2) levels in the atmosphere will, via the greenhouse effect, lead to a global warming. Humankind can respond to the prospective global change in several different ways. One possibility is through an increase in the size of the global carbon "sink." In this chapter we examine the effects of forests on climate change and the effects of climate change on forests. Forests can postpone the buildup of carbon in the atmosphere. Such a postponement may delay the advent of global warming and thus buy time for the substitution of nonfossil fuels as a more permanent solution to the global warming problem.

This chapter examines the mechanisms whereby changing CO_2 levels and global warming might affect forest growth and composition. It also examines the extent to which naturally generated climate-induced changes in forest area and forest cover mitigate or exacerbate the problem of rising atmospheric CO_2 levels. Increasing the forest stock by better management and decreased harvest from existing forestlands does not appear promising in light of our investigation. Neither does the natural generation of new forests in response to the climate change. Hence, the focus of our analysis is on the artificially established plantation forests.

The economic costs required to establish plantation forests in temperate and tropical regions are estimated. In addition, the economic uses to which the newly established forest stock might be put are investigated. These include industrial wood uses and also wood-fueled power generation. The possible effects of these higher stocking levels on world industrial wood markets and on investments in traditional industrial forestry activities are addressed and the broad economic implications examined. In neither case is the plantation likely to recover its costs. The question of the source of financing is addressed briefly and the possibility/necessity of foreign assistance is examined.

THE PROBLEM

The earth's climate may be undergoing a warming in response to the atmospheric accumulation of the greenhouse (radiatively important) gases (RIGs), at this time predominantly but not exclusively CO_2. The carbon content of the atmosphere is increasing annually by approximately 2.9 billion metric tons (gigatons [Gt]). This occurs in an environmental system where between 4.8 and 5.8 Gt of carbon in the form of CO_2 are released annually through fossil fuel combustion and cement production (Detwiler and Hall, 1988). Also contributing to this release are land-use changes that have eliminated large amounts of terrestrial biomass, particularly tropical forests, thereby freeing into the atmosphere the carbon that had been captive in the vegetation.

In principle, three basic strategies exist for responding to potential global warming: (1) prevent or limit the warming to nonthreatening levels; (2) allow the warming to occur and find low-cost ways to adapt; or (3) some combination of (1) and (2).

A number of ways have been suggested for preventing or moderating the emission of CO_2 into the atmosphere. In addition to the obvious approach of reducing carbon release into the atmosphere by dramatically reducing the use of fossil fuels and the conversion of forestlands, carbon sinks can be created or expanded. Such sinks could sequester the "excess" increments of CO_2 released that are currently responsible for the atmospheric buildup. Since forests experiencing net growth will sequester CO_2 from the atmosphere as part of the growing process, any buildup of forest biomass will reduce the buildup of atmospheric CO_2.

While the temperate forests may be roughly in carbon balance (Melillo et al., 1988) or in a modest carbon sink (Armentano and Ralston, 1980), the tropical forests are experiencing decline and are a source of carbon (Detwiler and Hall, 1988). The generation of net positive increments to the rate of accumulation of forest biomass would serve to sequester an increased portion of the free CO_2. Net additions in the carbon-sequestering ability of forests through a net buildup in forest timber inventories could be accomplished through (1) an expansion in the total forest biomass through massive investments in fast-growing plantation forests; (2) an increase in forest timber inventories, generated by increased management on existing timberlands, or a reduction in harvest, or both; or (3) an expansion of total forested area and biomass via a migration of natural forest into previously unforested land in response to higher temperatures, increased precipitation, and/or the fertilization effects of higher CO_2 levels. Any changes that result in increased forest biomass would contribute to a sequestering of at least a portion of the "excess" carbon released into the atmosphere. Similarly, any reduction in the rate of deforestation would reduce the amount of carbon accumulating in the atmosphere.

In this chapter we examine the mechanisms whereby climate changes forests and estimate the likely change in total forest area and biomass under the 2 x CO_2 scenario (see chapter 2 in this volume). This chapter also explores the potential of additional forest area and/or biomass growth to mitigate the buildup of atmospheric CO_2. Possible expansions of the forest area are explored. These could be caused by natural forest expansion generated by the warming process, more intensive management and/or reduced timber harvests, or the establishment of new plantation forests. Where plantation forests are involved, estimates are also made of the economic costs necessary to accomplish the desired sequestering of carbon. While it is obvious that many of the means to mitigate the buildup of CO_2 are not mutually exclusive and thus can be employed in concert, the analysis examines each of the options separately.

BACKGROUND

The Impact of Forests on CO_2 Levels

Over the centuries, the area of forestland has declined as populations have increased and lands have been converted from forests to other uses, particularly agricultural uses. Matthews (1983), for example, estimates the decline in global forestland at about 700 million hectares (ha) (1 hectare = 2.47 acres) or a reduction of about 15 percent from the preagricultural forest area. On stronger evidence, Olson et al. (1983) calculated a 50 percent decline in carbon stored in vegetation, most of it in forests. While the area of tropical forest is declining, the major declines in temperate forest area that occurred due to clearings in past decades and centuries have ceased. The temperate forest area is now stable. In fact, it may have increased modestly in recent decades. Data examined by Armentano and Ralston (1980) imply that net forest area has increased throughout the northern temperate zone, including North America, Western Europe, and Siberia.

The effect of the change in forestland area, however, need not translate directly into changes in the carbon sequestered by forests. Forest inventories vary with age and with tree species as well as site location and characteristics. Unmanaged forests may be thought to consist primarily of large mature trees. In fact, however, these natural systems range in age from infancy to senescence. Old forests, weakened by age, are ultimately destroyed by natural forces, only to regenerate once again. Fire, insects, and disease all contribute to the natural cycle of regeneration, growth, and decline. For example, until recently, several times more forest was destroyed by fire in the United States than at present and the natural pine forests of the U.S. South would not exist in the absence of a recurring fire cycle. Indeed, most forests have a measured fire return time, ranging from 10 to 1,000 years but normally 50 to 500 years. Hence, even a pristine landscape consists not simply of undisturbed, old-growth forests, but of a variety of forests at different stages of development and growth, thus embodying and sequestering very different amounts of carbon.

Initially, most forest clearing by humans was initiated by the desire to change use of the land, usually to agriculture. Hence, the biomass was largely destroyed, often by fire if feasible. The net stock of forest biomass was reduced thereby, liberating carbon into the atmosphere. However, over time, the production of industrial wood produced large volumes of poles, fences, rails, boards, timbers, and solidwood for construction of all types. Clearly, the wood used for these purposes and contained in structures, while no longer part of the forest, continues to sequester carbon. While the volume of wood in this form is obviously difficult to estimate, the stock of wood in this form has increased dramatically over time as has the volume of lumber and wood panels produced.

If we assume that one-quarter of the industrial wood harvested worldwide over the past thirty-five years remains in a solidwood form, then about 10 billion cubic meters (m^3) of wood exist in structures, furniture, and so forth. (Rotty, 1986, estimated 6 billion m^3 of solidwood remaining over a thirty-five-year period.) This volume is roughly equal to one-half the current total volume of growing stock in all the U.S. commercial forest inventory and would constitute a bank of roughly 2.6 Gt of carbon. However, this is only a very modest 0.17 Gt per year. Additional carbon is no doubt sequestered in wood and paper products and captured in landfills.

The relation of forest biomass to carbon sequestering is essentially a stock-flow problem. Net changes in the stock of forest biomass indicate the current flow of carbon being sequestered, while the total stock of forest indicates its carbon-sequestering capacity. Ultimately, the question of terrestrial carbon sequestering or release hinges on the total stock of carbon sequestered not only in the forest ecosystem biomass and soils, but also in the stock of industrial solidwood that remains. However, during transitions, the focus is on the net flux (flows) of CO_2 between forest ecosystems and the atmosphere (on the assumption that the carbon sequestered in industrial solidwood is small).

For forests and biomass to reduce the levels of CO_2 in the atmosphere, the inventory of forest biomass (and solidwood uses) must increase. The general approaches available are to increase the land area in forest biomass, increase the forest biomass per unit land area, or increase both. Mature fuelwood plantations will maintain equilibrium, absorbing and releasing offsetting amounts of CO_2. The creation of sustainable energy plantations with higher average biomass levels than those found in the previous land use, however, will result in a net sequestering of previously free carbon. Similarly, industrial forests could continue to produce the same volumes of harvested industrial wood (flows) while simultaneously having larger growing stock inventories. Ultimately, it is the size of the permanent change in the inventory stock that is important. The simple concept of plantation forests being used as a sink for carbon involves increasing the world's forest stock without a parallel increase in its harvests.

The Impact of Climate Change on Forests

There are a number of mechanisms whereby CO_2 and climate changes might affect forest growth and composition. These include the direct effects on physiologic, anatomic, ecosystematic, and geographic properties of tree growth induced by increases in ambient CO_2 concentration and air temperature and by shifts in precipitation patterns. The mechanisms also include the indirect effects of climate change on land use, that is, migration of high-intensity agriculture and concomitant release of current agricultural land for growth of forests. The eventual effects of such land-use shifts on the amount of carbon stored in vegetation are quite difficult to project and will not be considered further here.

Physiologic Mechanisms

The trees under discussion and, indeed, all green plants depend for life upon photosynthesis, the storage of solar energy when carbon from CO_2 in the atmosphere is united with hydrogen from water to form molecules of sugar (CH_2O) and elemental oxygen (O_2) (see chapter 2 in this volume). In addition to the CO_2 and water, photosynthesis requires warmth and nutrients, especially nitrates ($-NO_4$) and phosphates ($-PO_4$). The construction and life of tree cells occur during respiration in which oxygen combines with the previously synthesized sugar molecules to release stored energy. Carbon dioxide and water vapor are the byproducts of this process.

Too little warmth slows or stops photosynthesis and respiration. Required enzymes are inactive below a threshold temperature of 0°C to 10°C, depending on species (Steponkus, 1981). Photosynthesis and respiration increase with increasing warmth up to a temperature optimum, and then decline with further temperature increases. Temperature optima for respiration are normally much higher than those for photosynthesis. Thus, after a given temperature (compensation point) is passed, net photosynthesis (the difference between the energy fixed by photosynthesis and the amount lost by respiration) declines with continued increases in respiration. Photosynthesis essentially ceases altogether at about 38°C in boreal conifers, 43°C in temperate deciduous trees, and even higher in certain tropical trees (Kappen, 1981).

The availability of water in the soil also controls the processes of photosynthesis and respiration. When too little water is available, photosynthesis is slowed or halted. When soil is too wet, the flow of oxygen to the roots is impeded. Root respiration and the respiration-demanding uptake of nutrients is diminished.

Unlike annual plants that must survive the conditions extant during only one growth season, trees are adapted to surviving the wide environmental extremes encountered at one location for as long as 100 to 500 consecutive years. Thus, minor environmental fluctuations frequently have little lasting effect because trees are very conservative organisms. By definition, healthy trees at any given location are receiving adequate but not excessive warmth, water, and nutrients for survival and growth. Climate changes can be expected to shift this balance for individual trees, either with no effect when the broad requirements for survival and growth continue to be met or else with the effect of diminishing their photosynthetic potential, hence reducing the net uptake of atmospheric CO_2. Reductions of growth could force the death of trees during the 10 to 100 years that follow growth reduction (Solomon, 1986).

Although systematic changes from the current climate might reduce net photosynthesis, increases in atmospheric CO_2 concentration could increase it (see chapter 2 in this volume). Like warmth, water, and nutrients, CO_2 is required for photosynthesis. Greenhouse experiments indicate that photosynthetic rates of tree seedlings increase during short-term (minutes to days) CO_2 fumigations. The amount of water required to fix a given amount of carbon is also reduced as increased CO_2 concentrations close the leaf stomates through which gas exchange takes place (CO_2 into leaves, O_2 and H_2O vapor out of leaves). Unfortunately, there are few experiments on multiple-year fumigations and none that use mature trees. The few available results are ambiguous (B. R. Strain, Duke University, personal communication with A. M. Solomon, 1986) or suggest no permanent increase in photosynthetic rate or decrease in water use despite greater CO_2 concentrations (W. A. Oeschel, personal communication with A. M. Solomon, 1987). If such CO_2 "fertilization" does occur, it is unlikely to reach the values used by Solomon and West (1986) in modeling forest response to concurrent climate and CO_2 changes; for example, for a doubling of atmospheric CO_2 they assumed an 11 percent growth increase in conifers, 20 percent increase in deciduous trees, and an 18 percent decrease in water use in deciduous trees.

Anatomic Mechanisms

Trees of seasonal environments (the seasonally arid tropics; temperate and boreal zones) are also seasonal in their growth, sequestering most of the annual carbon fixed by photosynthesis at specific times of the year and thereby forming growth rings. Particularly in ring-porous wood (possessed by boreal conifers and about half of the temperate deciduous species), the growth rings are composed of light, thin-walled springwood (earlywood) cells and dense, thick-walled summerwood (latewood) cells. Although there is considerable variability in a given growth ring, latewood may contain three or four times as much material as earlywood (Panshin and DeZeeuw, 1964). The amount of material in earlywood cells--hence the carbon sequestered there--depends upon the amount of photosynthate available at the end of the previous growing season. In other words, it is a function of the total growth year (Fritts, 1976). In contrast, the latewood reflects growing conditions of the current spring, increasing with increasing spring warmth inducing greater spring photosynthetic rates, with earlier onset of summer weather inducing earlier shifts to latewood cell formation, and with mild summer drought to increase cell wall thickness (Conkey, 1986). Increasing spring warmth, earlier onset of summer weather, and mild summer drought are possible consequences of climate change (Manabe and Wetherald, 1986).

The amount of carbon storage that could result from enhancement of latewood density in temperate and boreal zone trees is difficult to project. Wood from most trees has a density of 300 to 800 kilograms per cubic meter (kg/m^3). Because latewood is two to three times as dense as earlywood (Panshin and DeZeeuw, 1964), little widening of the growth ring would be required to accommodate a significant increase in latewood carbon storage. Such a change might be first detected in an increase of the ratio of latewood to earlywood width and density.

Ecosystematic Mechanisms

From the beginning of tree growth on previously burned or farmed land, forest stands undergo a predictable succession of changes. Initially successful tree seedlings and saplings are tolerant of direct sunlight. They require few nutrients and grow rapidly, sequestering large amounts of carbon in short periods of time. As the trees mature, different seedlings and saplings appear. These grow more slowly, demand greater amounts of nutrients, and are less tolerant of sunlight. Ultimately, the most slowly growing species become dominant and retain dominance until mortality due to disease, or insects, or fires opening the sites to sunlight again. Intensive forest management is aimed at maintaining plots with these rapid-growth pioneer species and at harvesting these trees before they can be replaced by the slower growing shade-tolerant species. A climate change that kills large numbers of slowly growing late-successional trees will encourage growth of pioneer trees that store carbon at perhaps two or three times the rate of the shade-tolerant species (Solomon, 1986; Solomon and West, 1987).

Geographic Mechanisms

Tree growth is generally limited by lack of summer warmth at the high-latitude boundaries of species ranges. Northern boundaries of ecosystems and biomes are also thought to be warmth limited. As a result, and unlike most tree populations and communities, those growing near their northern range boundaries tend to experience increased growth during a warming of the magnitude projected by general circulation models of the atmosphere such as that of Manabe and Wetherald (1986). This effect should be expressed most clearly in the higher latitude forests (for example, northern boreal forests), where temperature increases are expected to be greatest, and where tree growth is now limited most by low growing-season temperatures.

The migration rates of tree species beyond their current boundaries in response to increasing temperatures and changing precipitation will be limited by supply of seeds. Solomon et al. (1984) calculated that the warming induced by a 2 x CO_2 scenario (see chapter 2 in this volume) during the next 100 years could occur at a rate ten times more rapid than that at which trees have migrated in North America during the past 10,000 years. Numerous barriers to migration in the form of agricultural fields, developed land, and road rights-of-way exist today. Hence, rates of migration would be much lower today than in the past. As a result, a rapid loss of tree species from landscapes can be projected in the absence of massive reforestation programs. The few tree species that might repopulate these areas would probably be those that possess small, light, wind-dispersed seeds that can be transported long distances (Davis, 1986). These are the pioneer species that grow rapidly. This feature of climate change could promote additional carbon storage in the short term.

Climate Change and Changes in Forest Types

Climate modelers generally agree that global warming will generate the greatest temperature increases in the high latitudes, while only modest temperature increases will be experienced in the tropics. Hence, the effect of warming on forests might be expected to be greatest on the high-latitude boreal forests of the northern regions (for example, those in Canada, Alaska, the Soviet Union, and the Nordic countries). Some observers expect the impact to be manifested through both the northerly expansion of forests into areas previously unforested and their higher growth rates (Kauppi and Posch, 1987; Hari et al., 1984). These high-latitude areas may be the most easily invaded by forests in the sense that competing human uses for the high-latitude lands are minimal.

The regional predictions of climate models are still very crude and must be treated with considerable skepticism. Nevertheless, some of the effects of global warming on North American forests can be projected. The response in eastern North America to a CO_2-induced warming, simulated by Solomon (1986), is a northerly shifting of the current forest zones with an overall expansion of forested area as the boreal forest migrates into unoccupied tundra. At the southern edges and on the western fringes, however, forestlands lose ground to nonforest vegetation. As a result, the volume of forest biomass increases by 30 to 50 percent in the North as the boreal forest expands and the southern edge of the initial boreal forest is eventually replaced by the cool temperate forest. Biomass is lost in the more southerly forests as they contract. According to this simulation, the total biomass for eastern North America ultimately declines.

Despite the regional projections, climate modelers and forest biologists have said little that is definitive as to whether global forests in total will expand, contract, or experience no net change under conditions of rising CO_2 levels and global warming. Later in this chapter we make a crude estimate of the possible effect of global warming on worldwide forest biomass and area.

FORESTS AS A CARBON SINK

In this section we examine the potential strength of global forests as a carbon sink. Three mechanisms for increasing forest stocks are examined: (1) natural increases in forest growth and biomass as the result of the climate change due to greenhouse warming; (2) an increase of forest stocking on existing forest either through increasing growth, decreasing harvest, or both; and (3) the establishment of rapidly growing plantation forests.

Natural Forest Expansion

The Gaia Hypothesis (Lovelock, 1979) proposes that the global biosphere, through natural processes, has the capacity to ameliorate changing pressures placed on the system. One mechanism whereby the biosphere might negate effects of CO_2-induced warming is by increased carbon sequestering in global forests. This could be accomplished if forests expand into regions where they do not now grow, and if photosynthesis rates and carbon storage are enhanced by warming, or perhaps in response to CO_2 enrichment of the atmosphere. The removal of this carbon from the atmosphere by these mechanisms could reduce warming, perhaps lowering global temperatures.

The potential for unmanaged forests to affect the carbon cycle in this way forms the subject of this section. First, we estimate the area new forests would have to cover in order to affect the rate at which atmospheric CO_2 concentrations change. Next, using the Holdridge Life Zone classification, we estimate how forest area and biomass might change in response to CO_2-induced climate changes independent of human interventions. We stress that forest ecologists have hardly begun to study whether global forested area and biomass would increase or decrease due to warming, much less to reach a consensus on this question. Based on a dynamic model of forest growth at a limited set of points on the landscape, Solomon (1986) and Solomon and West (1985, 1986, 1987) suggest that the most common forest response to initial warming will be tree mortality, with enhanced tree growth occurring in few places, and no change in growth or mortality in other places.

There is as yet only a very weak basis to support our reasoning. Changes unrelated to those considered by the specialists in each discipline are quite likely to determine the future course of forest growth. For example, technological change that produces agricultural land abandonment and subsequent forest growth may proceed at a rate great enough to mask any climate-induced changes in forest biomass. The only certainty is that "steady-state" climate and "equilibrium" forests are highly unlikely in the foreseeable future.

How Much Natural Expansion Is Required?

It is instructive to estimate the extent of natural forest expansion that would be required to mitigate the buildup of atmospheric CO_2 and to explore the likelihood that sufficient land area would be available should the forest-expanding effect of warming be greater than estimated. Assume for convenience that most of the expansion would take place in and around the current areas of the boreal forest--areas that are sparsely populated and have few competing human uses for land. Growth rates in boreal forests are relatively modest, averaging perhaps 2 m^3 per ha per year (Kauppi and Posch, 1987). If we accept an adjustment factor of 1.6 to account for the limbs and roots and an average of 0.26 tons of carbon sequestered per m^3 of forest growth, roughly 0.83 tons of carbon per ha will be sequestered annually. At this rate, a net addition of 3.5 billion ha of new forest would be required to sequester the requisite carbon. This represents more than a doubling of the world's area of closed forests and an increase in the world's total forest area to 7.5 billion ha from the present 4 billion ha. The requisite 3.5 billion ha of land is not available for naturally generated boreal forest expansion. Should the hypothetical expansion take place in a region with more rapid growth (for example, 10 m^3 per ha), only 700 million ha would be required, a large but more attainable area. However, such an area of productive land would probably be available worldwide only if large areas of other nonforested uses were to be suspended.

Change in Forested and Unforested Areas

An assessment of potential increased carbon storage in unmanaged vegetation must examine the global vegetational distributions and how these might change with CO_2-induced global warming and climate change. To date, Olson et al. (1983) have provided the most comprehensive and credible estimates of global distributions of large-scale vegetation groups (biomes) and of carbon in above-ground biomass. Forests cover about 42 percent of the earth's land surfaces (6.1 billion ha of forests out of the 14.5 billion ha of land surface), and they contain 483 of the 562 Gt (86 percent) of the globe's above-ground carbon (Olson et al., 1983). An estimated 73 percent of the carbon in the world's soil (927 of 1272 Gt) is in forest soils (Post et al., 1982). Hence, forests dominate the dynamics of the terrestrial carbon cycle.

The question we wish to address in this section is how forest area might change in response to CO_2-induced climate changes independent of the direct human interventions described above. The only formal approximation of that answer currently available can be derived from the output of the Holdridge Life Zone classification. This is a system that uses temperature and precipitation data to predict the distribution of life zones. It can also be used to assess probable shifts in biological communities in response to different climate scenarios. These results are mapped in Emanuel et al. (1985a); data based on an improvement to the standard Holdridge calculations is provided in Emanuel et al. (1985b). The improved maps appear in the inside front and rear cover of Bolin et al. (1986). The Holdridge system is imperfectly suited to our purposes, but it is the only spatially explicit and comprehensive work now available.

Based on data from approximately 7,000 meteorological stations, life zone classes were assigned to all 1/2 degree by 1/2 degree latitude and longitude land areas (cells) of the globe. Then the climate for each cell was changed, according to the Manabe and Wetherald (1986) projections for a doubling of CO_2. When the reclassified areas are compared with the original classes, an estimate emerges of changes that could be expected in life zone areas under stable climate (Emanuel et al., 1985b, table 1). Results are shown in table 8-1, columns 1 and 2. (Also see Batie and Shugart, chapter 9 in this volume, for an additional application of the Emanuel et al., 1985a, analysis.) Although Emanuel et al. provided thirty-seven life zone classes, they mapped only eighteen of these (Emanuel et al., 1985a, figures 2, 4). We combined classes to match their eighteen-class maps of life zone distribution (table 8-1, column 1).

Emanuel et al. (1985b) point out that the greatest changes in distribution of life zones occur in the high-carbon forests at the highest and lowest latitudes: boreal forests decline by 37 percent and tropical forests increase by 28 percent. This is all the more notable considering that the majority of global forests occur near the equator or in the boreal zones. The boreal forest that remains after warming is largely new, having replaced about 42 percent of the cells designated as tundra in the base case. Overall forested life zone area declines in the simulations by about 6 percent, equivalent to 444 million ha of forested land. Thus, if climate determines life zone distribution, and if life zones coincide with forested and nonforested land, then the climate scenario used implies that slightly less forested land would be found on an earth warmed by 2 x CO_2. Forest losses are made up in this analysis by increases in almost all nonforest (and low-carbon storage) life zones except tundra and temperate desert bush.

We may contemplate the processes or phenomena that might increase the areal extent of forests on the globe (that is, what information not considered in the Holdridge-based analyses could nullify the conclusion that forested area would be reduced under warming conditions). As noted, four mechanisms--physiologic, anatomic, ecosystematic, and geographic--could be considered in examining effects of climate on forests. The physiologic and geographic processes are particularly relevant here. The Holdridge scheme contains no

Table 8-1. Forested Area and Stored Carbon: Current and Future by Holdridge Life Zones

Area	1 x CO$_2$ area (10^6 km^2) [1]	2 x CO$_2$ area (10^6 km^2) [2]	Olson biomass (kg m^{-2}) [3]	1 x CO$_2$ carbon (Gt) [4]	2 x CO$_2$ carbon (Gt) [5]	Carbon difference (Gt) [6]
FORESTS						
Tropical wet[a]	0.387	0.413	20	7.740	8.260	+0.520
Tropical moist[b]	8.647	9.888	14	121.062	138.432	+17.374
Tropical dry[c]	9.992	14.033	10	99.920	140.330	+40.410
Subtropical wet[d]	0.510	0.281	13	7.650	4.215	-3.435
Subtropical moist[e]	11.453	9.096	7	80.171	63.672	-16.499
Tropical totals	30.989	33.711	31	316.543	354.909	+38.366
Warm temperate[f]	0.591	0.515	10	5.910	5.150	-0.760
Warm/dry temperate[g]	15.222	14.175	5	76.110	70.875	-5.235
Cool temperate[h]	11.287	11.627	10	112.870	116.270	-3.400
Temperate totals	27.100	26.317		194.890	192.295	-2.595
Wet boreal[i]	4.609	1.499	11	50.699	16.489	-34.210
Moist boreal[j]	12.654	9.381	8	101.232	75.048	-26.184
Boreal totals	17.263	10.880		151.931	91.537	-60.394
Total all Forests	75.352	70.908		663.364	638.741	-24.623
NONFORESTS						
Tropical thorn woodland[k]	7.066	9.189	3	21.198	27.567	+6.369
Temperate thorn steppe[l]	6.784	7.413	1.6	10.854	11.861	+1.007
Cool temperate steppe[m]	8.931	11.922	1.0	8.931	11.922	+2.991
Tropical desert bush[n]	13.654	16.290	0.4	5.462	6.316	+1.054
Temperate desert bush[o]	11.591	9.454	0.6	6.955	5.672	-1.283
Boreal desert[p]	1.309	2.591	1.0	1.309	2.591	+1.282
Tundra[q]	4.470	3.034	0.5	2.235	1.517	-0.718
Ice	2.218	0.567				
Total all nonforest	56.023	60.460		56.944	67.446	+10.502
Total forest and nonforest	131.375	131.368		720.308	706.187	-14.121

Note: The quoted classifications in notes a to q are from Olson et al. (1983).

Sources: For cols. [1] and [2], Emanuel et al., 1985b, table 1, and Emanuel et al., 1985a, figures 2, 4. For col. [3], Olson et al., 1983. Col. [4] is col. [1] x col. [3]; col. [5] is col. [2] x col. [3]; col. [6] is col. [5] - col. [4].

[a] Combines rain and wet tropical forest zones. "Evergreen equatorial forest."

[b] "Evergreen or deciduous forest."

[c] "Poor site or marginal tropical forest."

[d] Combines rain and wet subtropical forest zones. "Lowland and other tropical and subtropical broadleaved humid forest."

[e] Combines moist and dry subtropical forest zones. "Tropical dry forest and woodland."

[f] Combines rain and wet warm temperate forest zones. "Mostly temperate broadleaved forest."

[g] Combines moist and dry warm temperate forest zones. "Other semi-arid woodland or lowland forest."

[h] Combines rain, wet, and moist cool temperate forest zones. "Mixed woods, alternating evergreen and broadleaved forests."

[i] Combines rain and wet boreal forest zones. "Southern continental taiga."

[j] "Main taiga."

[k] Combines very dry tropical forest and tropical thorn woodland zones. "Tropical savannah and woodland."

[l] Combines subtropical thorn woodland and warm temperature thorn steppe zones. "Warm/hot grassland with more shrub."

[m] "Cool grassland."

[n] Combines tropical desert bush and desert with subtropical desert bush and desert zones. "Other desert and semi-desert."

[o] Combines warm temperate desert bush and desert with cool temperate desert bush and desert. "Cool semi-desert shrub."

[p] Combines boreal dry bush and boreal desert. "Low arctic tundra."

[q] Combines rain, wet, moist, and dry tundra zones. "Other high arctic tundra."

consideration of the process whereby physiological response to increased CO_2 in the atmosphere involves closing stomates and reducing water losses, which could allow trees to grow in steppe regions now limited to herbs and shrubs. The Holdridge projections indicate that current steppe areas (tropical thorn woodland, temperate thorn steppe, cool temperate steppe) cover about 23 billion ha--about 30 percent of the area now in forests. There is no way to estimate the possibility that such a mechanism would operate on a scale grand enough to affect such loss of steppe, but the possibility cannot be ruled out.

A geographically oriented process of potential importance that is absent from the Holdridge simulation is the role of moisture at lower latitude and dry boundaries of tree species and forest ecosystems. Emanuel et al. did not use the precipitation changes projected by Manabe and Stouffer (1980) for a 2 x CO_2 climate because of the inherent uncertainty of these projections. Although most climate models suggest decreased precipitation over large continental regions (see chapter 2 in this volume), enhancement of the hydrological cycle due to warming could also take place. If this occurs, and if the resulting increases in rainfall are not negated by increased evapotranspiration, then one might expect additional growth of trees in current areas of steppe and increased boreal forest growth in tundra, with much less concomitant boreal forest losses at southern forest boundaries.

Future land-use and technological changes could also increase the area of forests. For example, current trends to abandonment of marginal agricultural land (Delcourt and Harris, 1980), if continued, will certainly result in return of forests to previously forested land. The amount of land made available with improved fire suppression technology could also be important. In the absence of prairie fires, many tree species and communities can grow out onto the steppe. With increased development and population, national governments find fire suppression activities to be quite feasible and important to citizens. While forest fires burned some 2.5 million ha of U.S. forests in 1988, this is far below the average of 10 million ha per year in the 1920s. Thus, increasing effectiveness of wildland fire suppression seems likely in the future, further enhancing the spread of forests into unforested regions. Continuing destruction of tropical forests, however, opposes these trends.

Change in Carbon Density

Carbon sequestered as forest biomass may not decline when forest area declines because increases in area of carbon-rich forests, such as tropical wet forests, may offset or outweigh decreases in area of carbon-poor forests, such as the boreal forest zones. We present the estimates by Olson et al. (1983) of carbon density for each life zone in column 4 of table 8-1. Their values for areal cover of life zones or combinations of life zones are not included because of difficulties in matching Olson classes with Holdridge classes. However, Olson et al. estimates for areal cover are lower than the corresponding Emanuel et al. estimates. The Holdridge area estimates conform to "potential" vegetation, while Olson et al. provide areas of extant forests, minus areas in which man has replaced forests with crop, residential, and other uses. In addition, certain differences are impossible to reconcile in vegetation classes derived from differing criteria. However, the Olson and Emanuel classes are generally comparable for our purposes of determining the direction of change in carbon storage in the life zones.

Overall, forest carbon storage is predicted to decrease under a 2 x CO_2 climate from that of the base case climate (table 8-1, columns 5 and 6). The most important shifts in carbon densities due to warming occur again among tropical forests (57.784 Gt greater biomass in tropical dry and moist forests) and boreal forests (60.294 Gt less biomass in wet and moist boreal forests).

One problem with invoking the proposed CO_2 fertilization phenomenon is that the curvilinear and asymptotic relationship of photosynthetic rate with increasing atmospheric CO_2 concentrations should make any CO_2 fertilization decreasingly important with greater CO_2 concentrations (Regehr et al., 1975). As yet, the phenomenon of CO_2 fertilization has not been detected in trees, despite extensive searches for it in the field (LaMarche et al., 1984; Hari et al., 1984; Graybill, 1987; Parker, 1987) and in growth chambers (Doyle, 1987; Televski and Strain, 1987). The most likely response, if any, would be an increase in the rate of tree growth in forest gaps (Solomon and West, 1986), thereby closing gaps more quickly and decreasing the "carbon voids" in forest canopies. To significantly affect atmospheric CO_2 concentrations, annual carbon storage by trees would need to increase by only about 10 percent over the annual 31.5 Gt of net production estimated by Olson et al. (1983, table 2). A change of this magnitude has not occurred.

The results summarized in table 8-1 indicate that there is likely to be little natural net expansion in forest area or volume as the result of a global warming. Certainly, a climate-induced expansion of the 700-million hectare natural forest area as required in our estimate above is unlikely.

Managed Forests and Industrial Harvests

Another potential option for sequestering the excess atmospheric carbon would be by increasing the biomass growth of the world's existing forests through application of increased management and improved silvicultural practices and/or decreased harvesting. To increase forest growth enough to sequester all of the excess atmospheric carbon (2.9 Gt per annum), biomass growth for the 3,000 million ha of the world's existing closed forest would need to increase by an average of 4 m^3 per ha per year, or about 2.5 m^3 per ha per year for stemwood. This option would require an approximate doubling of the average rate of growth in all of the world's closed forests--temperate and tropical. The prospects of generating such a growth increase are discussed below.

Foresters have demonstrated their ability to increase forest productivity by intensive management. However, for the existing forests to sequester the atmospheric excess of carbon over the next several decades would require a rapid increase in the total forest biomass possible only if current growth rate and accompanying biomass accumulation are doubled.

Much of the increase in forest productivity is due to intensive management early in the growing cycle--planting that ensures a fully stocked stand, the use of genetically improved trees, weed control for newly planted seedlings, and so forth. These practices are currently applied in the process of reforestation after a harvest. But to double the growth of existing forests and significantly increase biomass accumulation in the next few decades would require a dramatic increase in management. Most of the increase in forest growth that would be required must come from increases to be induced in already established stands.

Fertilization is probably the most effective way to increase growth during the growing cycle. Ford (1984) and Nambiar (1984) cite experiments that show significant responses to fertilization in older stands. However, even if the growth rate were to increase 80 percent in response to fertilization (Beverge, 1984), its widespread application to the world's existing timber stands to accelerate growth and carbon sequestering is of questionable practicality because much of the closed forest inventory of the world is now in a mature or "overmature" state (e.g., Holowacz 1985, for the Soviet Union; Richardson, forthcoming, for China; Bonnor, 1982, for Canada). Even if fertilizer were added, little net growth would occur. Furthermore, a large fraction of the world's forests are in cool, high-latitude climates where the potential growth rate is limited by lack of warmth (Zavitkovski and Isebrands, 1983). Therefore, the burden of increasing overall world average forest growth would fall upon the young and middle-aged stands in warmer climates that are, in many cases, already growing relatively rapidly and may already be under management.

In summary, although forest management can help in increasing growth rate, forest management is most effective with initial forest establishment and in the early years of growth. Management has little to offer if applied to existing mature forest. Therefore, it appears that to double the growth rate of the world's existing closed forest while simultaneously maintaining and accumulating the increased biomass in a short period of time (one to two decades) is not technically feasible.

Dramatic increases in growth rates of many existing forests are unlikely, but forest biomass could be increased by lengthening industrial timber rotations through a temporary reduction of the harvest. As a limit, the maximum reduction from the industrial wood side would be accomplished through a complete cessation of commercial harvesting, thereby maintaining 1.5 billion cubic meters of timber that would otherwise be removed from the forests. The volume of biomass associated with 1.5 billion m^3 of stemwood is roughly 2.4 billion m^3 (using 1.6 factor for nonstemwood), and the carbon retained therein would be about 600 million tons (roughly 20 percent of the annual increment of carbon to the atmosphere). In point of fact, however, a substantial fraction of industrial wood already remains in solid form and decays only slowly over many years, and some nonstemwood parts of the harvested trees, such as the root system, also decay only slowly. Thus, the actual net retention of carbon in forest biomass following from a no-harvest policy would be considerably fewer than 0.6 Gt, perhaps in the neighborhood of 0.3 Gt, or roughly one-tenth of the annual accumulation of carbon in the excess atmosphere. Neither more intensive forest management nor reduced industrial harvests would increase the world's forest biomass enough to have more than a very modest impact in reducing buildup of carbon in the atmosphere.

Forest Plantations

Two estimates have been made recently of the forest area necessary to offset a portion of that buildup. Marland (1988, p. 53) estimates that as little as 500 million hectares of intensively managed rapidly growing plantation forests could sequester all of the 5 Gt or so of carbon, approximately the total amount released annually by the burning of fossil fuels. Marland's generally optimistic assumptions about growth rates, and particularly sequestering potential, lead to this relatively modest estimate of forestland required, especially given the immensity of the task of sequestering 5 Gt of carbon.

Attempting to address the same CO_2 sequestering problem, Woodwell (1987) estimates that 200 to 400 million ha of new, rapidly developing forest would be enough to withdraw between 1 and 2 Gt of carbon now accumulating in the atmosphere at current rates of emission.

To maintain the present level of atmospheric carbon, it is not necessary to capture all of the CO_2 generated by fossil fuel burning, as posited by Marland; 2.9 Gt would offset the increment now accumulating in the atmosphere at current rates of emission. However, maintaining the present level of atmospheric CO_2 requires capturing more than the 1 to 2 Gt posited by Woodwell.

The ability of forests to store large amounts of carbon and their importance in the global carbon cycle have led to the suggestion of massive afforestation to provide an additional carbon sink (Cooper, 1983; Brown et al., 1986; Marland, 1988). The ability of forests to sequester carbon is related very directly to biomass growth. Most growth figures used by foresters relate to stemwood and ignore branches, roots, leaves, and the like (Marland, 1988, p. 36). In our calculations, these are included in order to estimate carbon-sequestering capacity. Carbon is also sequestered in litter on the forest floor. The decomposition rate of litter is rather rapid, so after a few years the forest floor litter is likely to be in a steady state. Litter is ignored in our calculations.

Land Area Requirements

On reasonably good sites in the Pacific Northwest and the southern United States, a plantation forest can average growth of industrial wood (the stem) of about 15 m^3 per ha per year with a minimum of silvicultural inputs beyond planting (Farnum et al., 1983). Assume that 1 m^3 of stemwood is associated with 1.6 m^3 of tree biomass (including roots, branches, and so forth), and that 1 m^3 of biomass contains 0.26 tons of carbon (Brown et al., 1986). Then one ha of new forest will sequester about 6.24 tons of carbon annually. To sequester the 2.9-Gt annual increment of carbon in the atmosphere would require, therefore, about 465 million ha of new plantations. This is about 50 percent greater than the currently forested area in the United States and more than 15 percent of the current area of closed forest worldwide. Figure 8-1 helps put these numbers in perspective. The shaded area covers about 465 million ha. This is approximately 50 percent of the nonforested land area in

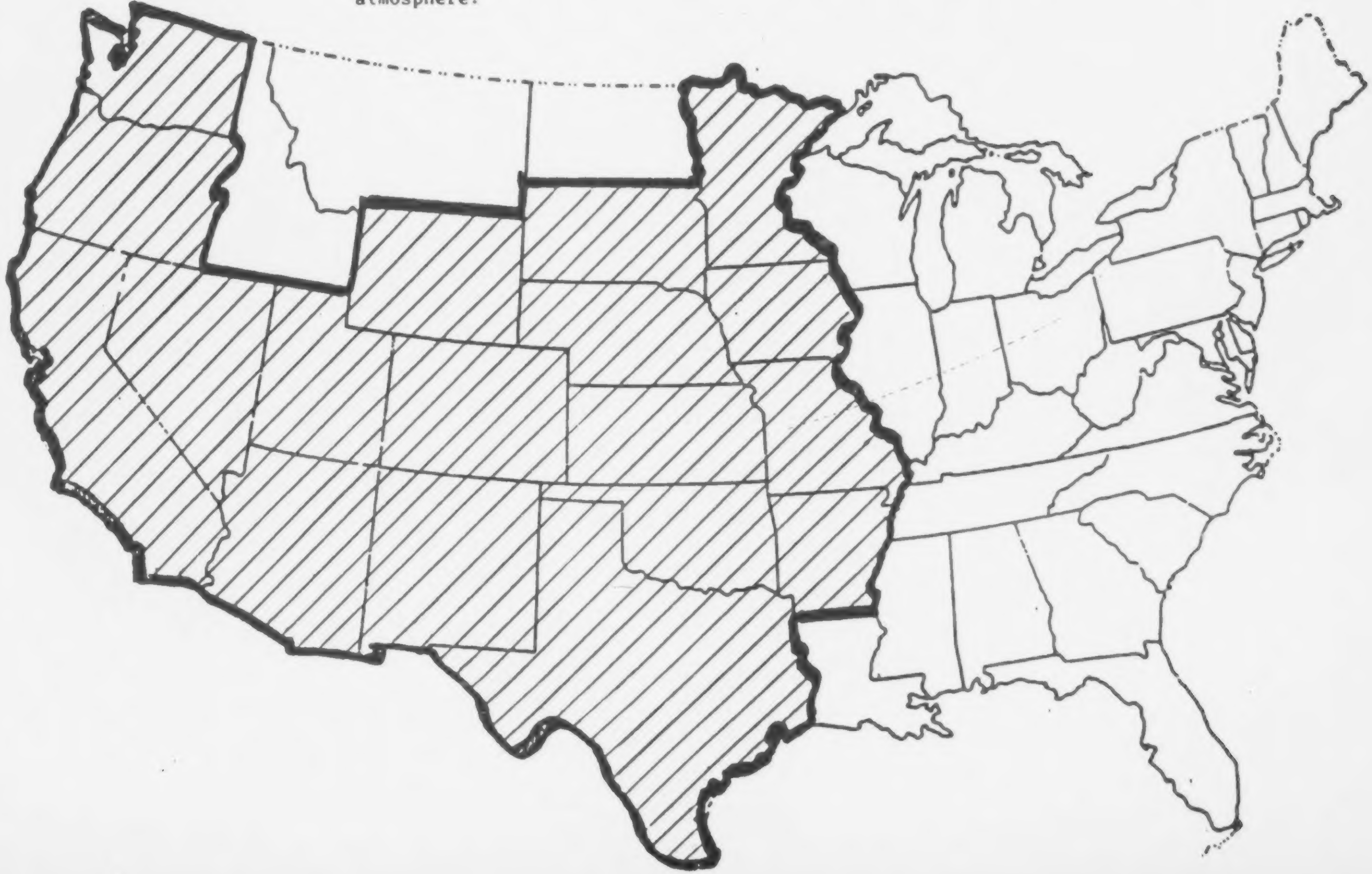


Figure 8-1. An area approximately equal to the 465 million hectares of newly planted forest that would remove the 2.9-Gt of carbon added annually to the atmosphere.

the United States (figure 8-1). An area this size of suitably productive land would probably require a worldwide search.

The FAO (1982) projected the total area of plantation forests in the tropics by 1985 at only 17 million ha. Earlier, Lanly and Clement (1979) estimated that the total area of manmade forests worldwide, both industrial and nonindustrial, in the mid-1970s was 90 million ha. The most recent estimate, by Postel and Heise (1988), puts total industrial plantations worldwide in the mid-1980s at about 92 million ha. Most of these plantations are found in the industrial countries in the temperate zone of the Northern Hemisphere, such as the Soviet Union, Japan, Western Europe, and the United States. Protection and other noncommercial forest plantations would add significantly to this total.

A forest plantation large enough to sequester all of the free carbon currently being absorbed by the atmosphere would be on a scale that would dwarf all previous forest plantation efforts. Is there enough suitable land to accommodate planting of this magnitude anywhere in the world? Much of the forestland of the requisite productivity is located either in the tropics or in the more southerly parts of the Northern Hemisphere temperate zone. Much of this land is already forested.

Another alternative might be to locate the plantations on less productive sites, perhaps in more northerly regions. However, in this situation tree growth would be less rapid; hence, the land area involved, and associated plantation establishment costs, would be greater. If lower productivity sites were to be used, the total land area required could easily be several times greater than we estimate.

Table 8-2 summarizes the areas of new or more rapidly growing forest required to stabilize atmospheric carbon dioxide for naturally induced forest expansion, increased growth of existing closed forests, and new plantation forests.

Table 8-2. Areas of New or Rapidly Growing Forest Lands Required to Stabilize Atmospheric Carbon Dioxide at Current Levels (annual atmospheric increase of carbon: 2.9 Gt)

To sequester carbon requires either:		No. of hectares
A. Warming-induced expansion of forests northward (assumes no forest decline elsewhere)		3,500 million
B. Increased growth of existing global forests (closed); need to increase their growth by 2.5 m^3/ha/year (current U.S.-wide average growth is 3.15 m^3/ha/year)		3,000 million
C. New fast-growing plantations		465 million
Cost:		
Temperate zone	$372 billion	
Tropics	$186 billion	

Economic Costs

The economic costs of undertaking a plantation effort of the magnitude just described are truly enormous. Establishment costs for forest plantations vary with location between $230 and slightly over $1,000 per ha. An average establishment cost of $400 per ha (Sedjo, 1983, p. 161) involves an initial investment of about $186 billion to establish the minimum area of new plantations required, 465 million ha. This does not include the costs of land procurement. The price of land is also likely to vary with location. In the United States today the average cost would be at least $400 per ha for land of the requisite productivity and could be as high as $1,000 per ha (Graham 1988). Hence, the minimum per ha start-up costs for CO_2 plantations in the United States could range from $800 to $1,400.

Using these minimal cost estimates, the total costs involved in establishing 465 million ha of carbon-sequestering plantations in the temperate zones might be $372 billion, almost 10 percent of the annual gross national product (GNP) of the United States. However, due to the tremendous land areas involved, valuable agricultural lands almost surely would be required and would demand higher prices. Thus, total costs would be significantly higher. To reduce land acquisition costs, plantations could be located on less productive forest sites. However, total plantation establishment costs would rise as more area would be required for planting and the sum of both acquisition and planting costs would increase. The costs of obtaining the land are not simply accounting costs that may be avoided by donations or expropriation. These costs represent real opportunities forgone. Land used as a carbon sink cannot be used to produce other socially useful products such as crops or livestock. However, such forest would generate some benefits other than carbon sequestering in the form of wildlife habitat, recreation, erosion control, and watershed stabilization.

The degraded lands of the tropics may also offer some opportunity for large-scale plantation. In many parts of the tropics such degraded lands have little if any alternative use. Thus, land costs are likely to be minimal. While the land area requirements are large, so too is the the land area potentially available. Grainger (1988) has estimated that 758 million ha of degraded tropical lands, including 203 ha of previously forested land in the humid tropics, have a potential for forest replenishment. However, the huge volume of land area required almost ensures that some low-productivity lands, perhaps in semiarid regions, will be required and thus drive up the total cost of land for establishing plantations. Plantation establishment costs in the tropics are similar to those in the United States. Recent data from Indonesia indicate that plantation establishment costs on degraded grasslands are about $400 per ha (JICA, 1986, p. 192).

While productivity on degraded lands is sometimes low, growth rates of 15 m^3 per ha per year and more are attainable on many tropical sites. If these cost and productivity figures are broadly representative of conditions in the tropics and if the land is essentially free, the total cost of establishing 465 million ha of plantation forests could be as low as $186 billion, about one-half the cost of a comparable carbon-sequestering plantation forest in the more temperate regions. Of course, these two options are not mutually exclusive. However, such plantation forests, no matter where they are located, would require significant follow-on costs of protection and maintenance.

Another consideration affecting the economic feasibility of the plantation approach is the question of what to do with the mature timber. Such a question would not need to be addressed if the purpose of the plantations were simply to buy time to develop a more adequate approach for dealing with carbon releases from fossil fuels. It becomes relevant only if the plantation approach were to be used for a period longer than a single rotation, which is typically thirty to fifty years.

If the plantation is to continue sequestering high levels of carbon over longer periods, the mature trees would need to be harvested to make way for a new, more rapidly growing second rotation. Cooper (1983), for example, suggests that shorter rotations may be necessary to keep the level of carbon sequestering high. However, he ignores the problem of disposing of the harvested timber. If the timber is simply treated as industrial wood, the large volumes harvested could severely disrupt world markets, depressing prices and generating a host of adverse impacts. In addition, much industrial wood is used for products such as paper that quickly decompose. The carbon-sequestering function is lost thereby. If the timber is harvested and the timber then inventoried, the sequestering function continues but the costs rise appreciably. Additional costs would involve harvest, transport, and inventory costs. Assuming a harvest rotation of thirty years involving 450 m^3 per ha, and a harvest and transportation cost of $15 per m^3, the total harvest-related costs are $6,750 per ha, exclusive of significant costs for timber storage. This suggests harvest costs thirty years hence for the 465 million ha totaling $3.1 trillion, in addition to substantial storage and preservation costs.

Cost Recovery from Forest Investments

Prospects are poor for recovering a substantial portion of the costs of plantation establishment by releasing mature timber from these forests onto world industrial wood markets. Commercial harvest of even a fraction of the mature timber of the plantations envisioned could easily swamp these markets. For example, the sustained yield harvest from the 465 million ha of new plantations would produce almost 7 billion m^3 of industrial wood. This volume is over four times the total world industrial wood harvest in 1985 (1.5 billion m^3). Such a volume of industrial wood would certainly disrupt wood markets dramatically and sharply reduce the price of industrial wood. At markedly lower prices, harvest and transport costs probably would not be covered by the market price for much of the timber.

The critical point is that the amount of forest required for carbon sequestering would create far more timber than could be absorbed by the world's industrial wood markets. Timber markets no doubt would return to an equilibrium even with radically lower prices, but those lower prices would not compensate private investors for their investments in industrial forestry. The lack of financial incentives would be translated into a decline in forestry investment and ultimately in the growth and productivity of the world's traditional industrial forests. With this would come an associated decline in the carbon-sequestering ability of these forests. Hence, some of the increased carbon sequestered by the newly created plantation forests would be offset by reduced carbon sequestering in the traditional industrial forests.

In the case of the naturally generated forests, the same possibilities for disrupting world wood markets exist. However, should most of the growth occur in the northern boreal regions distant from major world markets, the market disruption features would probably be small simply because the forest would be economically inaccessible. Warming in the high latitudes could, however, improve accessibility.

ADDITIONAL PROBLEMS ASSOCIATED WITH CARBON-SEQUESTERING FORESTS

The earlier discussion indicated a number of ways that the forest stock might be significantly increased and how, in so doing, it would serve as a carbon sink to mitigate the buildup of atmospheric carbon and thereby offset, to some degree, the anticipated global warming. Other issues include (a) the extent to which costs might be recoverable at harvest if the timber is sold for industrial wood, used as fuelwood for power generation, or otherwise utilized and (b) the problem of preventing the carbon sequestered in the forest from reentering the atmosphere if the wood is utilized.

An increased global stock of biomass is (for our purposes) a sufficient condition to the sequestering of a higher level of carbon. To the extent that a higher biomass stock is maintained, more carbon will be permanently sequestered. If the carbon sequestered in the increased biomass "originates" from the burning of fossil fuels, the carbon is simply shifted from a fossil fuel to a biomass residence. In a physical sense, a greater permanent stock of forest need not preclude greater industrial and fuelwood harvests. For example, an increased level of industrial or fuelwood use need not exacerbate the atmospheric CO_2 problem if a greater stock of forest is established and maintained to "feed" the increased use. In other words, the burning or destruction of biomass will not, per se, increase free carbon if the total stock of biomass is rising. Therefore, to the extent that an enlarged stock of forest is created for energy generation and the permanent stock requirement results in a net worldwide increase of biomass, the effect of biomass energy production would simply be to recycle carbon from the biomass to the atmosphere and back to the biomass.

The substitution of wood for fossil fuel combustion would have an advantage with regard to the carbon cycle: it would decrease the rate of carbon accumulation in the atmosphere resulting from energy production. This advantage could be maintained if the total stock of biomass did not decline as a result of utilizing the world's forest biomass stocks needed to feed the power generators.

The energy potential of the plantation-grown wood could be very large. We estimate that one year's wood energy potential is in excess of two years of energy generated by all of the coal-generated power plants in the United States. From an economic perspective, investments in energy forest plantations and power-generating equipment could provide some financial return. The output of the plantation becomes feedstock in the power generation process, replacing fossil fuels. But how financially competitive could wood-burning power generation be as a substitute for the current fossil fuel modes of energy production? Is it close enough to be justified on the basis of its positive climate-warming effects?

WHO PAYS AND HOW?

Market-generated financial incentives are unlikely to induce enough private investment in plantation forests to moderate significantly the buildup of atmospheric carbon. This is almost certainly true if the timber is to be used as industrial wood. Substituting wood for fossil fuels as feedstock to large boilers for power generation also is unlikely to be financially viable given current technology.

Probably the lowest cost locations for plantations are in the tropics. Should wood-fueled power stations be established, some of the costs could be offset by use of wood for power generation. Furthermore, foreign financial assistance could enable the industrial countries to finance directly a substantial portion of the plantation costs. This would provide an opportunity to contribute to Third World development while helping to mitigate the carbon buildup in the atmosphere and providing some relief to the global energy problem. However, even in concept, this approach has problems. Often the lands available for plantations are not situated close to the population centers needing power. Long-distance transportation of fuelwood or long-distance transmission of power would increase, immediately and dramatically, the costs of the useful power due to fuelwood's relatively poor energy density. Technology may eventually make low-cost, long-distance transmission of power feasible, but such technology is not currently operational.

Degraded tropical lands have few alternative uses. Hence, these locations are likely to be the low-cost locations for carbon-sequestering forests of the type suggested. In addition, the plantations will contribute to the rehabilitation of the degraded lands, lands that at some future time may be usable for other purposes.

CONCLUSIONS

In this chapter we examined the relationship between forests and the climate. In particular we investigated methods whereby increases in forest growth and the forest biomass might increase the terrestrial carbon sink and thus provide a means of delaying the buildup in atmospheric CO_2 and the onset and degree of global warming.

Plantation forests, especially if located on tropical lands with few alternative uses, may offer a relatively low-cost means for mitigating and postponing the buildup of atmospheric CO_2. A three- to five-decade postponement of global warming could provide society with enough time to develop energy source alternatives to carbon-releasing fossil fuels.

Three principal methods of increasing the global forest stock were examined in this chapter: (1) the establishment of massive areas of fast-growing plantation forests, (2) the use of forest management and a reduction in the harvest to allow a buildup of the stock of forest biomass, and (3) expansion of the forest system through natural generation of additional forests on previously unforested lands in response to environmental changes created by increased CO_2 levels and the attendant global warming. Based upon our preliminary assessment of these three possibilities, only the wide-scale establishment of forest plantations appears to have much potential.

Stabilization of atmospheric CO_2 at current levels would require a minimum of 465 million ha of new manmade plantations. A much larger area might be needed if some of the land was not productive, as is likely given the massive areas involved. Establishing tree plantations of this size would cost at least $372 billion--and probably significantly more in a temperate region like the United States where land has alternative productive uses. In principle, large areas of degraded lands in the tropics with few economic uses could be made available for afforestation. Thus, the tropics appear to offer a low-cost location, perhaps as low as $187 billion, for forest plantations sufficiently large to sequester the free carbon now accumulating in the atmosphere.

The problem of disposing of the plantation timber as it becomes mature was also considered. Two possibilities were examined: marketing the timber in the industrial wood market and using the wood as a substitute for fossil fuel in energy generation. In either case, much of the carbon sequestered in the wood would be liberated with its commercial use. However, the larger worldwide stock of forest associated with the newly created permanent plantations could ensure that a greater amount of carbon would be permanently sequestered. If significant portions of the new timber were made available to industrial wood markets, those markets surely would be disrupted, greatly depressing prices and inhibiting private-sector investments in forestry and forest plantations.

The option of using the timber in energy generation as a substitute for fossil fuels is examined briefly and appears promising. This approach has the advantages of reducing the use of fossil fuels and therefore the rate at which carbon is being freed from fossil fuels while simultaneously allowing for an increase in biomass stocks and the production of useful wood-generated power. The absence of this type of economic activity today suggests that the market does not currently provide the necessary financial incentives. Hence, subsidies almost certainly would be needed to achieve financial viability. The extent of such a subsidy warrants research.

The wood-growing possibilities for the tropics and Third World countries' increasing need for energy suggest the appealing possibility of linking these requirements together via multilateral economic assistance. A project of this type would address the world's carbon cycle problem, energy problem, and Third

World development problem in a manner whereby the industrial countries of the temperate zones would also assist in alleviating all three. To be sure, there are a number of potentially serious problems including questions of plantation location vis-à-vis the major energy-using centers of the Third World. Nevertheless, these possibilities deserve careful consideration.

REFERENCES

Armentano, T. V., and C. W. Ralston. 1980. "The Role of Temperate Zone Forests in the World Carbon Cycle," Canadian Journal of Forest Research vol. 10, pp. 53-60.

Beverge, D. I. 1984. "Wood Yield and Quality in Relation to Tree Nutrition," pp. 293-326, in G. D. Bowen and E. K. S. Nambiar, eds., Nutrition of Plantation Forests (London, Academic Press).

Bolin, B., B. Döös, J. Jäger, and R. Warrick, eds. 1986. The Greenhouse Effect, Climatic Change and Ecosystems (New York, Wiley).

Bonnor, G. M. 1982. "Canada's Forest Inventory 1981," Forestry Statistics and Systems Branch, Canadian Forestry Service, Department of Environment, p. 79.

Brown, Sandra, Ariel E. Lugo, and Jonathan Chapman. 1986. "Biomass of Tropical Tree Plantations and Its Implications for the Global Carbon Budget," Canadian Journal of Forest Research vol. 16, pp. 390-394.

Conkey, L. E. 1986. "Red Spruce Tree-Ring Widths and Densities in Eastern North America as Indicators of Past Climate," Quaternary Research vol. 26, pp. 232-243.

Cooper, Charles F. 1983. "Carbon Storage in Managed Forests," Canadian Journal of Forest Research vol. 13, pp. 155-165.

Davis, M. B. 1986. "Climatic Instability, Time Lags, and Community Disequilibrium," pp. 269-284, in J. Diamond and T. J. Case, eds., Community Biology (New York, Harper and Row).

Davis, M. B., K. D. Woods, S. L. Webb, and R. P. Futyma 1986. "Dispersal Versus Climate: Expansion of Fagus and Tsuga into the Upper Great Lakes Region," Vegetatio vol. 67, pp. 93-103.

Delcourt, H. R., and W. F. Harris. 1980. "Carbon Budget of the Southeastern United States: Analysis of Historic Change in Trend from Source to Sink," Science vol. 210, pp. 321-323.

Detwiler, R. P , and Charles A. S. Hall. 1988. "Tropical Forest and the Global Carbon Cycle," Science vol. 239, pp. 42-47.

Doyle, T. W. 1987. "Seedling Response to CO_2 Enrichment under Stressed and Nonstressed Conditions," pp. 501-510, in G. C. Jacoby and J. W. Hornbeck, eds., Proceedings of the International Symposium on Ecological Aspects of Tree-Ring Analysis. CONF-8608144 (Washington, D.C., U.S. Department of Energy).

Emanuel, W. R., H. H. Shugart, and M. P. Stevenson. 1985a. "Climate Change and the Broad Scale Distribution of Terrestrial Ecosystem Complexes," Climatic Change vol. 7, pp. 29-43.

_______. 1985b. "Response to Comment: Climatic Change and the Broad-Scale Distribution of Terrestrial Ecosystem Complexes," Climatic Change vol. 7, pp. 457-460.

FAO (Food and Agriculture Organization of the United Nations). 1982. "Conservation and Development of Tropical Forest Resources." Forestry Paper 37, Rome.

Farnum, P., R. Timmis, and J. L. Kulp. 1983. "Biotechnology of Forest Yield," Science vol. 219, pp. 694-702.

Ford, E. D. 1984. "The Dynamics of Plantation Growth," pp. 17-52, in G. D. Bowen and E. K. S. Nambiar, eds., Nutrition in Plantation Forests (London, Academic Press).

Forest Service, U.S. Department of Agriculture. 1982. "An Analysis of the Timber Situation in the United States, 1952-2030." Forest Resource Report 23, December.

Fritts, H. C. 1976. Tree Rings and Climate (New York, Academic Press).

Graham, David. 1988. Personal communication, Forest Investment Associates, Atlanta, Georgia, May 24.

Grainger, Alan. 1988. "Estimating Areas of Degraded Tropical Lands Requiring Replenishment of Forest Cover," International Tree Crops Journal, vol. 5 (1/2).

Graybill, D. A. 1987. "A Network of High Elevation Conifers in the Western U.S. for Detection of Tree-Ring Growth Response to Increasing Atmospheric Carbon Dioxide," pp. 463-474, in G. C. Jacoby and J. W. Hornbeck, eds., Proceedings of the International Symposium on Ecological Aspects of Tree-Ring Analysis. CONF-8608144 (Washington, D.C.. U.S. Department of Energy).

Hari, P., H. Arovaara, T. Raunemaa, and A. Hautojarvi. 1984. "Forest Growth and the Effects of Energy Production: A Method for Detecting Trends in the Growth Potential of Trees," Canadian Journal of Forest Research vol. 14., pp. 437-440.

Holowacz, J. 1985. "Forests in the U.S.S.R.," The Forestry Chronicle vol. 61, no. 5, October, pp. 366-373.

JICA (Japan International Cooperative Agency). 1986. "Technical Guidance for Afforestation on the Grassland in Benekat South Sumatra," ATA-186, April.

Kappen, L. 1981. "Ecological Significance of Resistance to High Temperature," pp. 439-474, in O. L. Lange, P. S. Nobel, C. B. Osmund, and H. Ziegler, eds., Physiological Plant Ecology I. Responses to the Physical Environment (New York, Springer-Verlag).

Kauppi, P. 1987. "Forests and the Changing Chemical Composition of the Atmosphere," in M. Kallio, D. P. Dykstra, and C. S. Binkley, eds., The Global Forest Sector (New York, Wiley).

------, and M. Posch. 1987. "A Case Study of the Effects of CO_2-Induced Climatic Warming on Forest Growth and the Forest Sector: A. Productivity Reactions of Northern Boreal Forests," in M. L. Parry, T. R. Carter, and N. T. Konijn, eds., The Impact of Climate Variations on Agriculture, vol. 1, Assessments in Cool Temperate and Cold Regions (Dordrecht, The Netherlands, Reidel).

LaMarche, V. C., D. A. Graybill, H. C. Fritts, and M. R. Rose. 1984. "Increasing Atmospheric Carbon Dioxide: Tree Ring Evidence for Growth Enhancement in Natural Vegetation," Science vol. 225, pp. 1019-1021.

Lanly, J. P., and J. Clement. 1979. "Present and Future National Forest and Plantation Areas in the Tropics," Unasylva, vol. 31, no. 123.

Lovelock, J. E. 1979. Gaia: A New Look at Life on Earth (New York, Oxford University Press).

Manabe, S., and R. J. Stouffer. 1980. "Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration in the Atmosphere," Journal of Geophysical Research vol. 85, pp. 5529-5554.

Manabe, S., and R. T. Wetherald. 1986. "Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide," Science vol. 232, pp. 626-627.

Marland, Gregg. 1988. The Prospect of Solving the CO_2 Problem through Global Reforestation. Report DOC/NBB-0082 (Washington, D.C., U.S. Department of Energy, Office of Energy Research).

Matthews, E. 1983. "Global Vegetation and Land Use: New High-Resolution Data Base for Climate Studies," Journal of Climate and Applied Meteorology vol. 22, pp. 474-487.

Melillo, J., J. R. Fruci, R. A. Houghton, B. Moore, and D. L. Skole. 1988. "Land-Use Change in the Soviet Union Between 1850 and 1980: Causes of the Net Release of CO_2 to the Atmosphere," Tellus vol. 40B, pp. 116-128.

Nambiar, E. K. S. 1984. "Plantation Forests: Their Scope and a Perspective on Plantation Nutrition," pp. 1-15, in G. D. Bowen and E. K. S. Nambiar, eds., Nutrition of Plantation Forests (London, Academic Press).

Olson, J. S., J. A. Watts, and L. J. Allison. 1983. Carbon in Live Vegetation of Major World Ecosystems. Report ORNL-5862 (Oak Ridge, Tenn., Oak Ridge National Laboratory).

Panshin, A. J., and C. DeZeeuw. 1964. Textbook of Wood Technology (New York, McGraw-Hill).

Parker, M. L. 1987. "Recent Abnormal Increase in Tree-Ring Widths: A Possible Effect of Elevated Atmospheric Carbon Dioxide," pp. 511-521, in G. C. Jacoby and J. W. Hornbeck, eds., Proceedings of the International Symposium on Ecological Aspects of Tree-Ring Analysis. CONF-8608144 (Washington, D.C., U.S. Department of Energy).

Post, W. M., W. R. Emanuel, P. J. Zinke, and A. G. Stangenberger. 1982. "Soil Carbon Pools and World Life Zones," Nature vol. 298, pp. 156-159.

Postel, Sandra, and Lori Heise. 1988. "Reforesting the Earth." Paper 83, April (Washington, D.C., Worldwatch).

Regehr, D. L., F. A. Bazzaz, and W. R. Boggess. 1975. "Photosynthesis, Transpiration and Leaf Conductance of Populus deltoids in Relation to Flooding and Drought." Photosynthetica vol. 9, pp. 52-61.

Richardson, Dennis. 1988. "Forestry in China - Revisited." Draft manuscript (February).

Rotty, R. M. 1986. "Estimates of CO_2 from Wood Fuel Based on Forest Harvest Data," Climate Change vol. 9, pp. 311-326.

Sedjo, Roger A. 1983. The Comparative Economics of Plantation Forests (Washington, D.C., Resources for the Future).

Smith, W. H. 1985. "Forest Quality and Air Quality," Journal of Forestry vol. 83, pp. 82-94.

Solomon, Allen M. 1986. "Transient Response of Forests to CO_2-induced Climate Change: Simulation Modeling Experiments in Eastern North America," Oecologia vol. 68 (Spring), pp. 567-579.

Solomon, A. M., and D. C. West. 1985. "Potential Responses of Forests to CO_2-induced Climate Change," pp. 145-170, in M. R. White, ed., Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health. Report DOE/ER-0236 (Washington, D.C., U.S. Department of Energy).

______. 1986. "Atmospheric Carbon Dioxide Change: Agent of Future Forest Growth or Decline?" pp. 23-38, in J. G. Titus, ed., Effects of Changes in Stratospheric Ozone and Global Climate, vol. 3, Climate Change (Washington, D.C., Environmental Protection Agency).

______. 1987. "Simulating Forest Responses to Expected Climate Change in Eastern North America: Applications to Decision Making in the Forest Industry," pp. 189-207, in W. E. Shands and J. S. Hoffman, eds., The Greenhouse Effect, Climate Change, and United States Forests (Washington, D.C., Conservation Foundation.

Solomon, A. M., M. L. Tharp, D. C. West, G. E. Taylor, J. M. Webb, and J. L. Trimble. 1984. Response of Unmanaged Forests to Carbon Dioxide-Induced Climate Change: Available Information, Initial Tests, and Data Requirements. Report TR-009 (Washington, D.C., U.S. Department of Energy).

Steponkus, P. L. 1981. "Responses to Extreme Temperatures: Cellular and Sub-cellular Bases," pp. 371-402, in O. L. Lange, P. S. Nobel, C. B. Osmund, and H. Zeigler, eds., Physiological Plant Ecology I, Responses to the Physical Environment (New York, Springer-Verlag).

Telewski, F. W., and B. R. Strain. 1987. "Densitometric and Ring Width Analysis of Three-Year-Old Pinus taeda L. and Liquidambar styraciflua L. Grown under Three Levels of CO_2 and Two Water Regimes," pp. 494-500, in G. C. Jacoby and J. W. Hornbeck, eds., Proceedings of the International Symposium on Ecological Aspects of Tree-Ring Analysis. CONF-8608144 (Washington, D.C., U.S. Department of Energy).

Woodwell, George M. 1987. "The Warming of the Industrialized Middle Latitudes." Paper presented at the Workshop on Developing Policies for Responding to Future Climate Change, Villach, Austria.

Zavitkovski, J., and J. G. Isebrands. 1983. "Biomass Production and Energy Accumulation in the World's Forests." The Seventh International FPRS Industrial Wood Energy Forum '83 1:12-22. Forest Products Research Society, Madison, Wis.

CLIMATE CHANGE AND U.S. FOREST MARKETS

James L. Regens[1], Frederick W. Cubbage[2], and Donald G. Hodges[3]

Atmospheric concentrations of greenhouse gases are likely to produce global-scale climatic changes over the next 50 to 80 years affecting important societal activities (Budyko and MacCracken, 1987). Substantial uncertainty surrounds the rate and magnitude of sub-global impacts, but existing studies suggest plausible impacts on growth patterns for managed forests (see Hodges et al, 1988). This study summarizes the results of such analysis for the dominant regions in the U.S., the South and Pacific Northwest, in order to identify policy responses that might ameliorate adverse implications of climate change for forestry.

PLAUSIBLE ECOSYSTEM AND FOREST MANAGEMENT IMPACTS

Limited data suggest plausible biophysical effects for entire forest regions due to the doubling of CO_2 and other trace gases (see Hodges et al., 1988). The potential impact on loblolly pine, the primary commercial tree species in the southern United States, and Douglas-fir, the major species in the Pacific Northwest, depends upon the composition of individual forest stands. Our study reveals that modeling responses to climate change by major commercial tree species involves an array of assumptions. These include projecting the frequency and distribution of severe climate events, determining the impact of climate change on forest insects and disease, estimating fire incidence, and linking the implications of those factors to forest management practices. For example, warmer weather might increase fire incidence but wetter winters might reduce forest fire problems, since most fires occur in the spring. And, if climatic changes occur fairly rapidly, forests might be more susceptible to insect and disease attack since generational succession occurs more quickly among pests than trees. As a result, to the extent that global climate change alters those ecosystems, forest management practices, especially stand establishment, stand manipulation and harvesting, will be affected.

The Southeastern United States. Increased summer temperatures and reduced precipitation will tend to modify forest management practices to enhance stand survival. For example, site preparation practices must minimize ecological damage to the more environmentally-sensitive sites typical of the

---

[1] Institute of Natural Resources, University of Georgia, Athens, GA 30602 (USA)

[2] School of Forest Resources, University of Georgia, Athens, GA 30602 (USA)

[3] Southern Forest Experiment Station, U.S. Forest Service, New Orleans, LA 70113 (USA)

Central Highlands because soil loss would reduce site productivity and moisture-holding capacity below their already low levels. A northward shift in the loblolly pine range would produce higher costs for stand establishment, maintenance, and harvest.[1] Assuming these additional costs were only $1 per acre per year, which seems extremely conservative, annual cost increases would exceed $100 million, in constant 1987 dollars.

The Pacific Northwest. The management focus for Douglas-fir also will change over the next 30-50 years but not primarily from climate change. Instead, new management regimes will emerge because of shifts from predominately old-growth to younger second-growth stands. Climate change, however, will be significant enough to create site-specific problems along the margins of the current natural range, especially water stress. Assuring adequate regeneration is likely to be the most serious problem in the marginal regions since seedling survival is largely dependent on favorable air and soil temperatures and rainfall. Planting methods already exist to regenerate such sites, but they may prove too expensive for the returns received. Moreover, those border regions cannot withstand intensive site-preparation practices which result in erosion or further loss of soil moisture.

IMPLICATIONS FOR THE U.S. FOREST INDUSTRY

Forestry traditionally has involved relatively long planning horizons and substantial uncertainty surrounding forest growth. The above discussion suggests that global climate change could alter significantly the resource management practices of U.S. forest products firms. Evaluating the impact of those effects on U.S. forest markets is essential for sound forest management.

To the extent the southern U.S. experiences altered precipitation patterns during the growing season, the resulting reduction in specific gravity for harvested timber would increase the overall volume of wood required by mills, decrease pulp yields, and reduce lumber quality and strength. Valuing product input changes that lack good biological dose-response functions is obviously tenuous. But increased wood fiber demand of even 1 or 2 percent would result in significant costs. And, individual pulp plant production would tend to decline slightly because less wood would be processed in the fixed digestor space. This is the case since digestor efficiency is, in part, a function of wood density with efficiency increasing as density increases so that yields would decrease compared to stated plant capacity. And, incremental expansions of existing mills must take into account chemical recovery capacity and energy balances, both of which are available only in lumpy units. Expanding plant capacity on a retrofit basis requires substantial redesign and large capital investments. Moreover, the retrofit option may not exist if processing plants relocate to acquire softwood supplies at competitive prices or due to sea level increases.

To the extent sea levels rise, as much as an additional 10 percent of total loblolly pine volume might be lost due to the flooding of the Coastal Plain. Table 1 illustrates the impact on total mill capacity from varying changes in sea level. Clearly, if severe enough, higher sea level gradients could force substantial mill relocation and/or increase costs for protecting low-lying coastal pulp mills.

TABLE 1

IMPACT OF VARYING INCREASES IN SEA LEVEL ON SOUTHERN AND NORTHWESTERN PULP AND PAPER MILLS

Elevation (m)	Mills Impacted (n)		Capacity (Tons/24 Hr)		Percentage Total Capacity	
	South	Northwest	South	Northwest	South	Northwest
3	16	1	16,720	475	14.6	1.7
5	18	2	18,945	925	16.6	3.3
7	23	6	23,305	5,435	20.4	19.4

Source: Adapted from McKeever (1987)

Note: Figures are cumulative. Percentage calculation based on total mill capacity of 114,315 tons/24 hours in the South and 27,980 tons/24 hours in Northwest.

Lumber yields should decline due to increases in the amount of earlywood harvested.[2] Such losses would involve physical damages from increased warpage and poorer drying of predominately earlywood lumber. Poorer quality lumber also may reduce market share for southern pine due to declining consumer preference for the product.

Massive migration of the southern pine resource northward might generate a corresponding shift in the industry's processing infrastructure as new plant construction occurs. Several factors would make such a shift costly. First, the southern pulp and paper industry is located predominately in the coastal areas which provide good access to water supplies and international ports. The southern mountains and Central Highlands lack readily available water supplies and well-developed transportation facilities which severely limits the physical desirability of those areas for plant locations. The high cost of building new greenfield pulp and paper mills also constrains relocation as long as existing capacity can be utilized. High entry costs for new mills (at least $500 million in current dollar terms) make such investments problematic, and even firms with adequate capital might lose competitive advantages to foreign producers having lower marginal costs. On the other hand, because sawmills require considerably less investment (approximately $10 to $20 million) and probably could shift with greater ease, the net impact should be less in the Pacific Northwest where the majority of plants are sawmills or other solidwood product producers.

Mills unable to relocate must pay more to transport logs or, eventually, cease business if costs become too great. This scenario is plausible given a recent study which concluded that southern forestry is likely to have stable supplies at best through the year 2030 (see U.S. Forest Service, 1988). Supply changes due to warming trends are certain to exacerbate any incipient problems. Marginal coastal mills typically would be affected by resource base shifts first. And, those remaining open would probably have to pay more for protection measures against rising sea levels.

The economic impacts of such shifts are obvious. Employment levels would decline in areas experiencing reduced plant output or closures. Table 2 reveals that such closures could have a significant impact in the South, where forest products manufacturing has been a major employer for the past 40 years. Direct wages formerly paid to employees of the firm and indirect wages for services and purchases made by the firm and its employees in the local community would be lost.

CONCLUSION

Estimating possible impacts of global climate change on U.S. forest markets is a significant research challenge. Data for economic valuation are scarce. As a result, the uncertainty surrounding economic consequences is substantial. The industry's capability to adapt to likely changes needs to be considered. Important factors include the impact of increased competition domestically for land and water resources and internationally for world market shares with foreign producers, as well as impacts on valuable non-market forest resources such as recreation and wildlife. Obviously, this creates problems for long-term forest management. Nonetheless, preliminary data suggest that prospective global warming, with its resultant changes in regional climatic conditions, will adversely impact forestry. At the very

TABLE 2

EMPLOYMENT IN MANUFACTURING LUMBER AND WOOD PRODUCTS AND PULP AND PAPER PRODUCTS, SOUTH AND NORTHWEST REGIONS

	Thousands of Employees				
State	1972	1976	1982	1986	Percentage Change (1972-1986)
SOUTH					
Alabama	38.4	39.9	38.0	50.4	31.2
Arkansas	29.7	28.5	27.4	31.5	6.1
Florida	31.6	28.9	30.9	41.2	30.3
Georgia	45.8	47.7	50.3	65.9	43.8
Louisiana	29.6	28.9	22.0	24.4	-17.6
Mississippi	28.4	26.3	25.5	30.8	8.4
North Carolina	45.2	49.4	49.7	58.4	29.2
Oklahoma	4.7	5.0	5.8	5.6	19.1
South Carolina	25.7	26.0	24.8	31.1	21.0
Tennessee	31.6	31.8	29.7	38.2	20.8
Texas	42.4	47.0	47.5	64.5	52.1
Virginia	34.4	34.3	32.8	38.4	11.6
TOTAL:	387.3	394.7	383.4	480.4	24.0
NORTHWEST					
California	90.3	104.2	83.7	99.0	9.6
Idaho	15.2	19.0	13.6	15.0	-1.4
Montana	9.2	9.3	6.8	8.1	-12.0
Oregon	84.7	87.6	65.2	72.9	-14.0
Washington	65.5	71.6	55,2	53.1	-19.0
TOTAL:	264.9	291.7	224.5	248.1	-6.4

Source: Adapted from U.S. Forest Service (1987); Warren (1987) least, the loblolly pine range will tend to move northward creating potential environmental and economic problems associated with stand establishment, forest growth, transportion to mills, and perhaps even mill closings.

There may be compensatory responses. Biotechnology may offset partially such impacts by developing seedlings that are drought resistant and highly responsive to increased CO_2 levels. Slash pine may expand northward, filling a void left by the retreating loblolly stands, and because slash pine generally is straighter, it may prove to be a superior replacement. For southern forests, it may become warm and wet enough for very fast growing species such as Eucalyptus or Caribbean pine to prosper.[3] Similarly, projections suggest that the benefits from increased CO_2 and the upslope movement of the winter snowpack in the Cascades will outweigh the harmful effects of increased temperatures and longer summer droughts. Market forces and engineering innovations may foster adaptation by the forestry sector to new, more efficient processing technologies. Moreover, because climate change is global in nature, U.S. forestry may adjust comparatively better with such an outcome giving American firms a competitive advantage despite increased costs.

On the balance, however, economic prospects for U.S. forest markets are likely to be negative. For example, Binkley (1987) projects that the impact of CO_2-induced warming on global forestry will cause income from timber sales to decline 20 percent in the eastern U.S. and 26 percent in the West by 2030.

Individual forest products firms face two different types of questions (see Sandenburgh et al., 1987). The first involves resource acquisition and management decisions. Typically, companies are likely to delay altering site management practices until changes in current operations seem warranted. In contrast, resource acquisition represents a more immediate concern. Firms may find it desirable to consider potential climate change impacts when purchasing or leasing timberland. The second type of decision involves research and development. Determining appropriate responses to climate change is difficult given the scarcity of reliable information, particularly on a subglobal basis. Thus, firms may conduct or fund research focusing on climate change's impact on forestry. However, based on the long time horizons for impacts and the forest industry's historical reluctance to fund substantial research programs (see Hodges and Harris, 1988), a significant commitment to climate change research is doubtful.

Given the uncertainty currently surrounding industry-specific assessments of climate change on a subglobal basis, from a policymaking standpoint, the key question is whether sufficient evidence exists to warrant direct governmental action. The most obvious options available include increasing energy efficiency, reducing the rate of deforestation in the tropics, and controlling global chloroflourocarbon emissions. Moreover, if those scientific uncertainties are to be diminished, an ambitious research effort is needed to delineate empirically the plausible effects of climate change as well as the implication of alternative policies aimed at reducing its undesirable consequences.

NOTES

1. Miller (1983) asserts that the northward-shift of the range generally would lessen the overall loblolly pine site index due to a shift to poorer sites competition with existing agricultural uses.

2. Latewood is produced during the dry summer months; earlywood is produced during the wetter spring months. Miller (1983) estimated that decrease of 5 to 7 feet in site index could occur throughout the region, which would result in a 10% yield reduction on pine land.

3. Eucalyptus is prone to cell damage from rapid drops in temperature not just cold temperatures alone. Given the U.S.'s continental climate, such changes would probably still occur despite higher mean regional temperatures.

REFERENCES

Binkley, C.S. (1987) "A Case Study of the Effects of CO_2-Induced Climatic Warming on Forest Growth and the Forest Sector: Economic Effects on the World's Forest Sector," in M. L. Parry, T. R. Carter, and N.T. Konjin, eds., The Impact of Climatic Variations on Agriculture (Dordrecht, Netherlands: Reidel).

Budyko, M.I. and M.C. MacCracken (1987) "US-USSR Meeting of Experts on Causes of Recent Climate Change," Bulletin of the American Meteorological Society 68(3):237-243.

Hodges, D.G., J.L. Regens, and F.W. Cubbage, (1988) "Evaluating Potential Economic Impacts of Global Climate Change on Forestry in the Southern United States, "Resource Management and Optimization 6(3):

Hodges, D.G. and T.G. Harris, Jr. (1988) "U.S. Forest Products Research: Trends and Outlooks," Forest Products Journal 38 (7/8):26-32.

McKeever, D.B. (1987) The United State Woodpulp Industry. Forest Products Laboratory Resource Bulletin FPL-RB-18 (Madison, WI: U.S. Forest Service).

Miller, W.F. (1983) "Alternative Futures for Resource Management," pp. 17-28 in Water--A Resource in Demand Southern Cooperative Series, Bulletin 288 (Starkville: Mississippi Agricultural and Forestry Experiment Station, Mississippi State University).

Sandenburgh, R., C. Taylor, and J.S. Hoffman (1987) "How Companies Can Respond to Rising Carbon Dioxide and Climate Change," in W. Shands and J. Hoffman, eds., The Greenhouse Effect, Climate Change, and Forest Management in the U.S. (Washington: Conservation Foundation).

U.S. Forest Service (1988) The South's Fourth Forest-Alternatives for the Future (Washington: U.S. Forest Service).

Warren, D.D. (1987) Production, Prices, Employment and Trade in Northwest Forest Industries, First Quarter, 1987. (Portland: U.S. Forest Service).

IMPACTS OF GLOBAL CLIMATE CHANGE ON WATER RESOURCES

(By Jeffrey A. Zinn, Specialist in Natural Resources Policy, Congressional Research Service)

Global warming is likely to alter the supply and quality of water resources, but more exact patterns can not be predicted at this time. In many areas, supplies are likely to be reduced because of the combination of temperature increases, a northern expansion of arid areas, a smaller snowpack and an earlier spring runoff. Some of the basic relationships between global warming and water resources are shown in the schematic on the next page.

In the first article, Frederick and Gleick emphasize that existing institutions may be the main constraint to dealing with these problems. They call for greater flexibility in the water resources institutional framework, echoing the conclusions of many of their peers. These individuals all conclude that water resource systems must be "more resilient and robust" than in the past. These systems have been designed to accommodate the range of variation in precipitation and temperatures that have occurred—they were not designed to accommodate the range of changes that a growing number of scientists say are possible in the future.

These potential changes are especially threatening to the current pattern of economic development in the arid West. Revelle and Waggoner explore the possible effects of one scenario, an increase in average temperature of 2 degrees Centigrade and a decrease in average precipitation of 10 percent, on the water supplies and requirements in seven water regions in the West. Already in some areas, a shortage of water (which has not been connected to the possible effects of global warming) has led to a growing number of public and private market decisions to more effectively allocate existing resources among competing users. Global warming, if it does occur, is likely to greatly expand the area affected by these conflicts and exacerbate them further.

Scientists have run scenarios to see how various climate forecasts will affect rainfall and the distribution of water. Among the issues that have surfaced are:

- Implications of the lack of a winter snowpack and larger runoff during the winter months and less runoff during the months when irrigation waters are needed;
- Implications of a greater demand for water by all users because of higher air temperatures, and higher evaporation rates, even if rainfall increases;
- Implications for in stream uses, including navigation, recreation and habitat; and
- Implications of replacing freshwater by brackish and salt water in low-lying estuarine areas.

In anticipation of these potential problems, policy analysts are calling for greater flexibility, both in structural activities such as the construction of water projects, and in the legal framework used to allocate water. In addition, such changes will give renewed impetus to water conservation efforts, where research has repeatedly demonstrated that great savings can be realized.

Finally, it is likely that the patterns of use could be altered in areas where supplies or quality is most constrained, and conflict is most likely to result. Some of the potential conflicts that have been identified include:

- Between in-stream and off-stream uses;
- Between water supply and flood control in the West;
- Between recreation and other uses;
- Between thermoelectric power production and other uses; and
- Between agriculture and other off-stream uses.

Hanchey and his colleagues discuss the effect of this uncertain future on planning activities in the Nation's largest water resource management agency, the U.S. Army Corps of Engineers. They point out that the Corps does not have a clearly-stated policy that recognizes global warming, but reassure us that it is being factored into planning efforts within the agency. They conclude with an identification of a series of needs to improve water resource planning in the future.

DRAFT MANUSCRIPT--ch. 10 in
Greenhouse Warming: Abatement
and Adaptation

10

Water Resources and Climate Change

Kenneth D. Frederick
Peter H. Gleick

A greenhouse warming is certain to have major impacts on both water availability and water quality. Temperature, precipitation patterns, evapotranspiration rates, the timing and magnitude of runoff, and the frequency and intensity of storms will be affected by increasing concentrations of carbon dioxide and other trace gases. A rise in sea levels associated with a global warming could threaten the freshwater supplies of coastal communities. And changes in temperature and rainfall levels will affect the demand for water, especially for irrigation.

There is now a consensus among climate modelers that a global warming will increase global precipitation. An increase 1.5 to 5.5 degrees Celsius (°C) in average global temperatures (the range expected to result from an equivalent doubling of atmospheric carbon dioxide) is expected to accelerate the hydrologic cycle and thereby increase global precipitation by an average of 7 to 15 percent (Schlesinger, 1988).

RISKS TO WATER SUPPLIES ASSOCIATED WITH CLIMATE CHANGE

Water problems, whether they involve floods or drought, are regional in nature. Consequently, changes in regional precipitation patterns are far more important than changes in the global average. Unfortunately, regional changes are difficult to estimate because global climate models have only coarse spatial resolution and relatively simplistic hydrologic parameterizations (World Meteorological Organization, 1988). General circulation models do indicate some regional changes, such as increases in precipitation toward the poles, but the range of likely changes in average annual precipitation for any given region could be on the order of plus or minus 20 percent.

Changes in runoff are the direct result of changes in evaporation (which is strongly influenced by temperature) and in precipitation. Relatively small changes in temperature and precipitation can have large effects on runoff in arid and semiarid regions. A simulation study of the Great Basin in the United States, for example, showed that with a 2°C increase in temperature, a decrease in precipitation of only 10 percent led to a 17 to 28 percent decrease in runoff, while an increase in precipitation of 10 percent caused runoff to increase by 20 to 35 percent (Flaschka, Stockton, and Boggess, 1987). In another simulation Nemec and Schaake (1982) showed for the Pease River Basin in Texas that a temperature increase of 3°C and a 10 percent decrease in precipitation led to a decrease in runoff of 50 percent, while an increase in precipitation of 10 percent led to a 35 percent increase in runoff. Similarly, Gleick (1986, 1987) modeled California's Sacramento Basin and found that a temperature increase of 2°C and a 10 percent decrease in precipitation caused an 18 percent decrease in annual average runoff. These results are summarized in table 10-1.

Although detailed regional hydrologic predictions are not yet available from general circulation models, some additional generalizations can be made. There is evidence that runoff may increase in high latitudes due to increased high-latitude winter precipitation but may decrease in summer in mid and low latitudes as temperatures and evapotranspiration increase (Shiklamanov, 1987; World Meteorological Organization, 1988). Perhaps more importantly, regions where runoff comes largely from snowmelt are likely to see a distinct shift in the relative amounts of snow and rain and in the timing of snowmelt due to higher temperatures. The resulting changes in runoff patterns could greatly alter the likelihood of flooding and the availability of water during peak-demand periods such as the irrigation season. This type of seasonal effect was identified by Gleick (1988a) for basins in the western United States and has now been identified in China (Shi Yafeng, Director, Nanjung Institute of Geography, Nanjung, China, personal communication with Gleick, 1987), Canada (Cohen, 1986), and Europe (Bultot et al., 1988).

Gleick (1988a) showed, for example, that in the Sacramento Basin in California, a 2°C increase in temperature (with no change in precipitation) increased winter runoff nearly 10 percent and decreased summer runoff by 22 percent. An increase of 4°C increased winter runoff by 34 percent and decreased summer runoff by 62 percent. Such changes will have extremely important ramifications for both winter flooding and summer irrigation. Further studies are needed to explore the impacts of these runoff changes on water resource management.

Threats to water resources will also come from rising sea levels due to thermal expansion of the oceans and increased melting of glaciers and land ice. A sea-level rise of 20 to 80 centimeters (cm) over the next fifty years is likely (Hoffman, 1984; Vellinga, 1987). As sea level rises, salinity levels in bays, inland waterways, and coastal aquifers will rise, threatening the water supplies of such coastal cities as San Francisco and Miami. In some regions rapid local subsidence from groundwater pumping or other causes will worsen the problem. In San Francisco Bay, an apparent sea-level rise of 17 cm over the last century is the result of an actual sea-level rise of approximately 12 cm and ground subsidence of about 5 cm, and the problem of subsidence is considerably worse in other areas such as New Orleans. Yet, as chapter 4 (in this volume) by Gjerrit Hekstra suggests, the water supply problems associated with rising sea levels pale in comparison to the societal and environmental costs that would result from flooding in densely populated, low-lying coastal areas such as Bangladesh.

In summary, water resource planners and managers must expect global climate changes to cause significant changes in the overall hydrologic cycle: shifts in annual precipitation and runoff, altered seasonality of hydrologic processes, changes in the extremes of storms, and, perhaps, new threats to water quality. In the absence of clear regional predictions, it is only prudent to examine ways to increase our capacity to respond to such changes by both increasing the resilience and flexibility of our existing physical and management structures and decreasing our dependence on levels of water use developed under supply conditions that may prove to have been unusually favorable and to be impractical to sustain.

COPING WITH HYDROLOGIC CHANGE

The existing infrastructure for storing and transporting water was planned and designed and continues to be operated under the assumption that future levels and patterns of precipitation, runoff, and evaporation will be similar to those experienced in the past. The prospect of future climate change, however, raises questions as to whether this is still a useful assumption to guide the design and operation of water supply systems.

Infrastructure

The long construction periods and lifetimes of many water projects suggest that early planning for the hydrologic impact of climate change can prevent project failure when conditions change and thereby can save expensive redesign or reconstruction. But, as noted above, there is great uncertainty as to how the hydrology of specific regions will be affected by a greenhouse warming. In many instances, even the direction of change is unknown; the normal uncertainties about climatic extremes are compounded under conditions of changing climate. Yet knowing if streamflow or other hydrologic factors will exceed or fail to reach certain values is critical to the economic and social evaluation of a project and to estimates of the consequences of the failure of that project. Both building for changes that never materialize and failing to build facilities to deal with changes that do occur are costly prospects. As the uncertainties increase, the stakes associated with this dilemma grow.

Most water resource systems are designed to be "robust" and "resilient." Robustness refers to the ability to respond to the range of uncertainties associated with the variability of future events. Resiliency refers to the ability both to operate under a range of conditions and to return quickly to designed performance levels in case of failure (Matalas and Fiering, 1977).

The vulnerability of water supplies to future climate change will in many ways be similar to existing vulnerabilities to climatic variability and extremes. Climatic extremes are most often manifested as unusual flows or altered timing of flows, such as seasonal floods, persistent droughts, major storms, and the early or delayed onset of a range of meteorological events. Although reservoirs and aqueducts are designed to be robust and resilient, they still fail occasionally due to extreme events. Such failures are undesired, but they are recognized to be a result of normal uncertainties about hydrologic events. The planning goal should be to build projects to protect against extreme events up to the point where an additional dollar spent on protection no longer reduces the expected cost of failure by at least a dollar.

Critics have blamed the U.S. Army Corps of Engineers for overdesigning their water projects. In its defense, three Corps officials contend, "The design criteria merely reflected the conventional engineering approach of focusing on an extreme event or condition, e.g., as the critical drought period of record or the probable maximum flood or hurricane. This approach accounted for the unknown climate variability and the uncertainty that the existing data did not reflect the true range of possible events" (Hanchey, Schilling, and Stakhiv, no date, p. 6). As a result of these practices, the officials note, water resources agencies have effectively been designing large hydraulic structures and water control systems almost as if anticipating climate change.

This optimistic view of the ability of the existing infrastructure to handle the impacts of climate change has support among researchers. Matalas and Fiering (1977, p. 109) concluded: "It is comforting to recognize that most large systems contain so much buffering and redundancy that resilient design can be operationally achieved without recourse to sophisticated or elaborate projections about the climate." Nevertheless, the magnitude of future climate change could well produce alterations in the hydrologic cycle that overwhelm the safety margins of existing systems.

In addition, a strategy of building such redundancy into future water supply and control projects will become increasingly costly. Rising water project costs would appear to be inevitable for three reasons. First, the best reservoir and dam sites available for increasing a stream's safe yield (the quantity of water that can be supplied with some high degree of probability) are developed first. Thus, subsequent additions to a system's capacity require utilizing less desirable sites with higher costs per unit of storage. This trend is evident in table 10-2, which suggests that reservoir capacity per unit volume of dam declined thirty-five-fold in a comparison of large reservoir projects constructed in the United States before 1930 with those constructed in the 1960s.

Second, Langbein (1959, p. 4) demonstrated that "water control by storage follows a law of diminishing returns. Each successive increment of control (safe yield) requires a larger amount of reservoir storage space than the preceding increment." Moreover, at some point the net yield actually declines as evaporation losses from the additional storage more than offset any gains from the additional reservoir capacity. Within the conterminous United States, Hardison (1972) found that safe yield peaks when storage is in the range of 160 to 460 percent of a region's average annual renewable supply. But the gains in yield from additional storage may be very low even when capacity is well below 160 percent of the average annual flow.

Third, the opportunity costs of storing and diverting water (for example, the recreational and wildlife benefits forgone by the loss of instream flows) rise as the amount of water left in the nation's streams declines. The traditional practice of ignoring the impacts of water projects on instream water uses ended with the National Environmental Policy Act of 1969, which requires all federal agencies to give full consideration to the environmental implications of their actions. The higher value placed on instream water use has been evident over the last two decades in the strength and success of the resistance to new storage and diversion projects.

While the costs of adding to supplies and increasing control over water through structural measures are rising, the benefits of additional infrastructure may also increase if future climate change produces climatic extremes far greater than those evident in the historical hydrologic record. Expectations of climate change are likely to affect the design of new facilities; they could also increase the demand for new water projects. Thus, reliance on structural approaches in the face of climate change presents the grim prospect of paying much higher costs to meet growing water demands and to limit risks of system failure. Alternative approaches, especially improving the management of the existing infrastructure, will become increasingly attractive and essential for providing secure water supplies in the future.

Managing the Infrastructure for More Water and Greater Security

Even in the absence of any major climate change caused by the greenhouse effect, the high financial and environmental costs of developing new supplies are forcing the United States to look beyond the traditional structural solutions for meeting growing water demands. Uncertainties as to how an anthropogenically induced climate change will alter the supply and demand for water strengthen the case for seeking ways to improve the management of existing water supply facilities.

Reservoirs have traditionally been managed independently, each under its own set of objectives and operating rules. Yet operating water supply projects as integrated systems may provide a low-cost way to increase safe yield in some areas without large additional investments in infrastructure. Joint management of the facilities of independent water suppliers may make it possible to improve significantly the supply capabilities of each individual supplier within a region with relatively little new investment. Such benefits have been achieved in the Washington, D.C., metropolitan area where joint operation of the systems of the three principal water supply agencies increased drought-condition water yields by more than 30 percent while saving between $200 million and $1 billion compared to the proposed structural solutions. Two studies by Sheer (1986) suggest that major benefits from improved management are also possible in regions with very different water supply characteristics. According to Sheer, conjunctive use of surface and groundwater supplies in Houston, Texas, could increase system yields by 20 percent; joint management of supplies in the North Platte River Basin could reduce water shortages by about 30 percent.

Despite the potential benefits, water supply projects are rarely operated as integrated systems. Institutional factors such as separate ownership of facilities, multistate jurisdictions, and water laws are often obstacles to the consideration of integrated solutions to water problems. Yet the success of integrated management in Washington, D.C., and a growing recognition that structural solutions alone will no longer suffice should help overcome such obstacles. The nation's principal federal agencies in charge of constructing water projects are at least talking about the need to give greater emphasis to improved water management. The key conclusion of Assessment '87 by the U.S. Department of the Interior's Bureau of Reclamation (1987, p. i) is that "the Bureau's mission must change from one based on federally supported construction to one based on effective and environmentally sensitive resource management."

A recent paper by senior officials of the U.S. Army Institute for Water Resources stresses the need to place greater emphasis on management measures to complement their infrastructure in meeting the problems caused by extreme events and the uncertainties stemming from the prospect of climatic change. These officials concluded:

> Society cannot afford to build "fail-safe" projects anymore.
> It isn't economically efficient, either for water supply,

> flood control, or hurricane storm protection on coastal shorelines. Notwithstanding the Corps' past history of a reliability-based analysis for extreme events, their design concept has increasingly become "safe-fail". It is a strategy of designing flood protection for less than the extreme event of record. A structural measure (levee, channel) is complemented by emergency management plans that mitigate the damages of designed . . . failure of structural solutions. In other words local flood protection could conceivably be designed for a 20 to 50 year level of protection, as long as there is a complementary flood warning and evacuation plan. These complementary mechanisms represent an important contributing factor to the robustness and resiliency of water resources management systems, and are specially relevant to adaptation under climate uncertainty. . . . While hydrologists may not be able to explicitly factor in the anticipated variability of climate change, especially if they rely on empirical rather than causal models, water resources planners and engineers can implement a wide range of management measures that increase the robustness and resiliency of solutions that can operate under an anticipated range of climate uncertainty. . . . (Hanchey, Schilling, and Stakhiv, no date, p. 7)

Institutional factors are hardly the only obstacles to developing more efficient water-management practices. Climate-induced changes in the time of flows complicate the development of proper operating rules for reservoirs. In winter in California, for example, some reservoirs are operated to maintain sizable flood control storage. Yet summer irrigation demands require that these same reservoirs be as full as possible to provide a reliable supply for the dry season. This produces a conflict between the risks of flooding if the reservoirs are filled too early and the risks of shortage if the major runoff season ends before the reservoirs can be filled (Gleick, 1988b). Extreme weather conditions have led to adjustments in the operating rules for some of California's reservoirs in the past. For example, the severe 1976-77 drought prompted changes designed to make the system more resilient to droughts. These rules, however, led to a higher risk of flooding during high-runoff years in the early 1980s, and the operating rules were changed again. An increase in the variability of precipitation or a change in its seasonality would exacerbate the problem of deciding when to begin filling a reservoir and how large a flood-storage volume to maintain.

Demand Management

Water planners have traditionally taken a supply-side approach to meeting the growing demands for municipal, industrial, and irrigation uses. Water use was projected to grow virtually in step with population and income levels, and the resulting projections were treated as virtual requirements to be met regardless of cost. Prices were believed to have no significant effect on water use. Thus, until recently, concerns about the adequacy of future water supplies invariably led to plans for new dams, reservoirs, pumps, and canals. But, as noted above, exclusive reliance on new infrastructure to meet water demands that are unconstrained by price has become infeasible and environmentally unacceptable. The previous section described how improved management might increase the reliable yield of a given supply system. This section considers the use of demand management to balance water use with available supplies.

The need for demand-side management is gaining acceptance, but there are differing views as to how it should be implemented and the role it should play. The basic approaches to curbing water use involve, first, regulations (that is, command-and-control measures) and, second, prices and markets. The water planner who expects supplies to meet unconstrained demand levels under all but the most severe drought conditions would only reluctantly resort to demand-side management. Regulatory measures are likely to be viewed as a necessary, but last-ditch, tool for bringing water use into line with supplies during periods of extreme drought. Temporary drought-emergency measures would probably start with appeals for voluntary conservation and, if necessary, include restrictions on nonessential uses such as lawn watering and car washing. If it is necessary to curb the long-term growth of demand, this might be done by imposing water conservation standards for appliances and showerheads under the regulatory approach.

Economists, on the other hand, are likely to view demand-side management as a means of both allocating increasingly scarce water resources among competing uses (even during normal hydrologic periods) and eliminating construction of water projects for which the social costs exceed the expected benefits of the additional water. Marginal-cost pricing of publicly supplied water and market transfers of water rights are the means proposed for achieving these objectives. Prices, whether set by monopolistic suppliers to reflect the marginal costs of supply or determined in competitive markets, provide the incentives to encourage conservation, develop new supplies, and direct scarce water resources to their most valuable uses.

Despite the professed advantages of the economists' view, skepticism, and even outright rejection, of their prescriptions for using prices and markets to allocate water resources are widespread. Underlying these doubts are beliefs that water use is not responsive to price and that the characteristics of the resource make it difficult, if not impossible, to establish competitive markets in water. The rarity of well-functioning water markets reinforces these doubts. Yet, in view of the potential efficiency and flexibility of market solutions to economic problems, it is useful to consider whether the absence of water markets reflects fundamental factors rooted in the nature of the resource or institutional constraints to their operation.

Efficient markets must satisfy at least two conditions: there must be well-defined, transferable property rights in the commodity being traded, and the buyer and the seller must bear all the costs of the transfer. These conditions are not easily fulfilled for at least four reasons. First, it is difficult to establish clear and transferable property rights to groundwater and surface water supplies that vary over time and flow from one property to another. Second, even when streamflow rights are established, transfers of water to different uses and locations are likely to affect people other than the buyer and seller because of resulting changes in the quantity, quality, location, or timing of return flows. Third, some of the products of water resources, such as the amenities associated with a free-flowing stream, are not marketed. If left to private incentives and markets alone, there will be underinvestment in these outputs. And finally, since it is generally impractical to have more than one supplier, the price of water to domestic and commercial users is not set by market processes but by utility managers or regulatory agencies.

In spite of the importance of natural market failures, water marketing does occur and, with appropriate policies and institutional arrangements, could play a more important role in adjusting to changes in the supply and demand for water. Indeed, the flexibility of markets to adjust to unanticipated changes in supply and demand would be particularly helpful in coping with the hydrologic impacts of climate change. Currently, the relevant policies and institutions often discourage rather than encourage water marketing. The riparian doctrine, which grants the owner of land adjacent to a water body the right to use water as long as the use does not unduly inconvenience other riparian owners, provided the earliest basis for state laws controlling surface waters. By attaching the water right to the land, the riparian principle of water rights prohibits the establishment of water markets. The seventeen western states have abandoned, or at least modified, this doctrine in favor of the doctrine of prior appropriation, which establishes the basic principle of "first in time, first in right."

This step was important for creating definable property rights in water. But other features of western water law confuse the character of these appropriative rights and lessen their transferability (Frederick, 1984). For example, these rights are commonly encumbered by provisions restricting use to beneficial purposes or to certain locations. Sale of a water right has in a few instances even been interpreted under the beneficial-use provision as grounds for forfeiting the right. Thus, owners may be reluctant even to consider selling water rights for fear that beneficial-use provisions of state water codes would be used to invalidate their rights.

All western states permit water transfers under certain conditions so long as the rights of third parties are not impaired. Usually, however, third-party impacts are important, and satisfying the third-party provisions of state water laws involves costly and lengthy judicial or administrative procedures that are incompatible with the operation of efficient markets. Creating more efficient ways of handling third-party interests is perhaps the most difficult and important consideration for the emergence of more effective markets in water.

Traditional water-pricing practices and opportunities for introducing demand-side management in the urban and agricultural sectors are discussed below.

Urban Water Use

Planning and pricing within the urban water industry have emphasized increasing supplies at the lowest possible cost in order to meet projected levels of water use. Traditionally projected to increase in line with population and economic growth, water use has been treated as a necessity that is unresponsive to price. Water rates have been set just high enough to cover average costs plus some capital for future expansion and a fair return to investors.

This average-cost pricing policy has important implications in an industry where the costs of developing new supplies are rising sharply. Efficiency requires the expansion of supplies up to the point where the marginal cost of supplying another unit is just equal to the additional value of that last unit. Consumers will continue to use more of a good until the value they receive from another unit declines to their cost (that is, the price) of purchasing another unit. Thus, the price reflects the marginal value of water. In the water industry, where the costs of developing new supplies are relatively high and the price is based on average costs, the marginal costs of new supplies exceed the marginal benefits. Consequently, average-cost pricing practices have resulted in the construction of water projects for which the costs have far exceeded the benefits.

Marginal-cost pricing is generally rejected by the water industry on two grounds--a belief that use is not responsive to price and an expectation that the implied price levels would be unacceptably high. Adoption of marginal-cost pricing could indeed result in some sizable price increases just because the costs of developing new supplies are generally so much higher than the average costs, which are heavily weighted by the low costs of the earliest developed supplies. But contrary to the assumption traditionally employed by the industry, there is considerable evidence, much of it reviewed by Gibbons (1986), that such price increases would have significant impacts on water use.

The potential role of marginal-cost pricing in balancing water supplies with projected demands has been examined for southern California. Applying marginal-cost pricing to the additional supplies that the Metropolitan Water District hopes to get from an expansion of the State Water Project would increase consumer prices by about 75 percent. (The Metropolitan Water District is a wholesale supplier of water to six southern California counties; the State Water project is a long-term effort to construct a major aquahut and storage system to move large quantities of water from the well-watered northern parts of the state to the arid central and southern parts.) Conservative estimates of the price elasticity of demand (the percentage change in the quantity demanded resulting from a percentage change in price) suggest that a price increase of this magnitude would reduce water use by enough to offset the entire projected growth in demand for the region from 1985 to 2000 (Wahl and Davis, 1986, p. 117).

Agricultural Water Use

Four of every ten liters of fresh water withdrawn from the nation's streams and groundwater aquifers in 1985 were used for irrigation. In the arid and semiarid seventeen western states, irrigation accounts for nearly eight of every ten liters withdrawn and nine of every ten liters of consumptive use (the portion of the water withdrawn that is not available for reuse due to contamination, evaporation, or other losses) (Solley, Merk, and Pierce, 1987). Their prominence in current water use makes irrigators particularly susceptible to the impacts of climate change on future supplies.

Easy access to very low-cost water was an important factor in the expansion of irrigated agriculture during the first two-thirds of this century, and the increasing costs and scarcity of water have contributed to the recent decline in total irrigated acreage in the West. Indeed, past changes in regional irrigation developments can be explained in large part by changes in the availability and cost of water (Frederick, 1988). There are several reasons for expecting irrigation water use to be particularly sensitive to the cost of water. First, water costs are likely to comprise a higher proportion of total costs for irrigators than for most water users. Second, in comparison to most domestic, commercial, and industrial uses, irrigation water often goes for relatively low-value uses that are likely to be abandoned or modified if water prices rise significantly. And third, irrigators commonly have a variety of alternatives for reducing water use in response to rising costs. For instance, water losses might be reduced by lining canals or adopting more efficient irrigation systems. Crop yields might be maintained or increased even though less water is applied by scheduling irrigations so that water is applied only when it can be used most effectively by the plant. And switching to less water-using crops or varieties may become profitable as water becomes more expensive.

Although irrigators have many options for conserving water short of abandoning irrigation, they often have little incentive to do so. Rights to use surface water have been granted free by the western states to anyone making "beneficial" use of the resource. The principle of "first in time, first in right" gives the earliest appropriators the right to withdraw their full share even during periods of shortage. As the largest and commonly the earliest water users, irrigators own high-priority rights to much of the West's water for as long as they continue to use it. Since they pay nothing for the water itself, their water costs reflect distribution and perhaps storage costs. But even these costs are subsidized for federally supplied irrigation water. For many irrigators water costs do not depend on the amount actually used. Consequently, irrigators with senior water rights are likely to be isolated from the increasing scarcity and value of the resource unless they are able to sell some or all of their water, for even if the water is free, an opportunity to sell all or part of the right creates an opportunity cost reflecting the potential sale price. Opportunity costs introduce incentives to conserve. Increased opportunities to transfer water within and among regions and better incentives to conserve would facilitate adjustments to climate change, especially in regions where water will become scarcer.

Technological Change

The development and adoption of technology are strongly influenced by the prices of the principal factors of production (for example, land, labor, and water) as producers seek to substitute relatively abundant and inexpensive inputs for scarce and costly ones (Hayami and Ruttan, 1985). At least until the last decade or so, water was treated as the most abundant and inexpensive resource; saving water was not an important consideration in either the development or the adoption of production techniques and management practices. This attitude still prevails where costs do not depend significantly on the quantities of water used and the holders of the water rights lack opportunities to sell conserved water.

As the largest user, the agricultural sector is the prime candidate for saving water in the nation's arid and semiarid areas. Moreover, as noted above, irrigators have a number of alternatives for curtailing use when there is sufficient incentive to do so, and research is expanding their options.

As recently as two decades ago, researchers as well as irrigators saw little reason to conserve water. Consequently, emphasis on water conservation within the agricultural research community is relatively new. The increased concern over water use within the agricultural research community is illustrated by changes in the objectives of plant breeding in arid areas. In the 1960s, researchers sought mainly to develop seed varieties that would maximize yields under conditions of plentiful water. More recently, considerable effort has been devoted to increasing yields under conditions of less or uncertain water supplies. Investments in research are helping to develop inputs, such as more water efficient seed varieties, and management techniques that will better enable farmers to adapt to more expensive and scarcer water. Other developments include chemicals to reduce transpiration without yield loss and irrigation and agronomic management practices that increase yields per unit of water under a range of circumstances. Many such developments have already been adopted where water is expensive.

Plant varieties that help individual irrigators adapt to scarcer and more expensive water will also help entire water resource regions adjust to the hydrologic impacts of climate change. More generally, technologies that increase yields per unit of applied water or reduce crop losses under low-water conditions tend to produce social benefits commensurate with the private returns (assuming that the water is not used to produce surplus crops). For some water-conserving technologies, however, there may be large differences between their net private and social benefits.

Because one farmer's runoff or losses may be another farmer's supplies, more efficient use of water on individual farms may not lead to equivalent increases in a system's or a region's efficiency. From the perspective of an entire water resource region, the important inefficiencies result in losses that are not recovered for later use through return flows or groundwater recharge. By contrast, any water that is not effectively utilized by crops is lost as far as the individual irrigator is concerned. As water becomes more expensive to the irrigator, the incentive to reduce on-farm water losses rises, even if that water is fully recovered by others through return flows. In this situation, the private benefits of applying water-conserving technologies exceed the social benefits.

On the other hand, environmental impacts tend to narrow, and may even reverse, the gap between the net private benefits and the net social benefits of technological alternatives. Concentrations of salts, sediment, and agricultural chemicals are higher in return flows than they are in water applied to a field. Thus, technologies that improve on-farm efficiency are likely also to improve downstream water quality. But the environmental benefits and costs of the alternatives are borne by downstream users rather than by the irrigator.

Even though computations of farm-level water savings generally overstate the net additions to a region's water supply, the value of the savings to the irrigator determines whether an individual will invest in water conservation. Based on recent sale prices, water sold for municipal uses in the West might command more than $80 per 1,000 cubic meters (about $100 per acre-foot). Permanent rights to an annual supply commonly sell for well over $800 per 1,000 cubic meters ($1,000 per acre-foot) (Western Network, 1988).

Irrigators can generally conserve water at costs well below these levels. Significant water savings at comparatively low cost are often possible on farms using gravity irrigation, the system employed on more than 60 percent of the West's irrigated lands. With an unimproved gravity system only about half of the water delivered to the farm--and perhaps much less if the terrain is uneven or the soil is sandy--actually reaches the plant. Under conditions characteristic of many irrigated areas, investments in laser-leveling of fields to reduce runoff or tailwater recycling to capture runoff for subsequent reuse might improve on-farm efficiency by 20 to 30 percent at costs of $40 per 1,000 cubic meters or less ($50 per acre-foot) (Frederick, with Hanson, 1982). Irrigation efficiencies of about 80 percent can be achieved even on sandy, hilly soils with sprinkler irrigation systems. While the combined investment and energy costs are considerably higher for sprinkler systems, they often produce significant labor savings as well as water savings. Drip or trickle irrigation systems virtually eliminate water loss, but their investment costs are likely to be at least three times those of most sprinkler systems.

Other than the minimum requirements for survival, water use can be reduced through water-conserving investments and technologies. The potential impacts on overall water supplies within the nation's arid and semiarid regions of water conservation by nonagricultural users are likely to pale in comparison to those of water conservation by the agricultural sector. Yet conservation by municipal and industrial users, which are discussed below, may be essential for meeting long-term demands within the nation's urban and industrialized areas. Even the mining sector, which accounts for less than 1 percent of the nation's total withdrawals, can be important for balancing local supply and demand.

Municipal water serves a variety of uses, including drinking, cooking, bathing, lawn watering, swimming, and firefighting. Some of these uses (especially those outdoors) are responsive to water prices, but very little of the response is likely to stem from technological change. At the prevailing levels of use, consumers' adjustments to price increases are likely to represent making do with less water rather than adopting new water-conserving technologies. Water-efficient dishwashers, showers, and toilets can reduce domestic water use, but water prices alone are unlikely to offer consumers sufficient incentive to demand them or producers incentive to develop and produce them. A strong conservation ethic or, more likely, use of building and manufacturing regulations may be required to ensure the development and widespread adoption of such technologies.

Where climate change results in increased water scarcity, technological changes that reduce desalting and recycling costs can help municipalities adapt. Desalinization of seawater is currently too expensive for all but the most water-scarce regions and the most high-value uses, and in the absence of a major decline in energy costs or an unexpected improvement in desalinization technologies, it is likely to remain so for the foreseeable future. On the other hand, some regions have large quantities of brackish water with salt concentrations that are well below those found in the oceans but are still too high for municipal use. As desalting and recycling technologies improve, they are likely to become increasingly important means of supplementing municipal water supplies. Where health or psychological factors make this water unsuitable for drinking, it might replace other supplies used for irrigating golf courses, public roadways, and crops. Farmers, however, are likely to find such water too expensive if it is priced to recover the costs of desalting and recycling. More promising technological developments for using low-quality water in agriculture may lie in developing crop varieties with a high tolerance for salt and improving water management practices for irrigating with such water.

Self-supplied industrial water accounts for about 45 percent of the nation's total withdrawals of fresh water but less than 10 percent of the consumptive use. Cooling water for thermoelectric plants accounts for about 85 percent of all industrial withdrawals, but only about 2 percent of that water is used consumptively. And only about 4 percent of the water withdrawn for other industrial water uses (such as manufacturing, refining, and food processing) is consumed (Solley, Merk, and Pierce, 1987; Solley, Chase, and Mann, 1983). Consequently, even though evaporative cooling technologies and the recycling of industrial process water greatly reduce withdrawals for industrial use and are relatively common, these changes have little impact on overall consumptive water use. The principal impacts of water-using technologies within the industrial sector are on the quality rather than the quantity of water. Moreover, water costs have little influence over the choice of industrial technologies because they are rarely more than a small part of a firm's total costs. Adoption of water-conserving technologies by industry is apt to be motivated more by environmental regulations or institutional obstacles to securing adequate water supplies than by strictly economic considerations.

VULNERABILITY TO CLIMATE CHANGE

The preceding discussion suggests a wide range of options for dealing with climate-induced changes in water supplies. With perfect foresight, wise planning, and flexible institutions, many regions should be able to adapt to likely changes in supplies with little economic or social pain.

Improved management of existing supplies, marginal-cost pricing and water marketing to encourage conservation and reallocation of supplies in response to changing conditions, and development of water-saving technologies can provide considerable flexibility for adaptation. Unfortunately, foresight is invariably flawed, and water planners and institutions have not yet fully absorbed the significance of, nor adjusted appropriately to, the changes in the supply and demand for water that have occurred over the last several decades. These shortcomings suggest that it may be useful to consider the capacity of various water resource regions to adapt to large changes in water supplies in the absence of new infrastructure or institutional changes or technological developments.

Two indicators of the vulnerability to hydrologic change of the major American river basins are presented in table 10-3. The first indicator, the ratio of maximum storage volume to mean annual renewable supply within the basin, is one measure of a region's ability to withstand prolonged drought or flood. Large reservoir capacity relative to average annual streamflow provides protection against short-term droughts and flooding. Conversely, where this ratio is small (perhaps below 0.6), climate-induced reductions in water or changes in the frequency or intensity of droughts and floods may be strongly felt.

This measure alone can be misleading, however, since it neglects the demand side of the picture. Thus, the second measure in table 10-3, the ratio of demand to available supply, also provides important information. Where this ratio is high, existing supply is sensitive to growing population, growing industrial and commercial demand, and climatic fluctuations. Alaska, for instance, has essentially no storage. But since demand for water is negligible relative to supplies, Alaska is not currently susceptible to drought. On the other hand, even though the Lower

Colorado Basin has by far the highest ratio of storage to average supply, it is vulnerable to the impacts of drought because consumptive use in the basin is 96 percent of average renewable supply. Szesztay (1970) suggests that water is a critical factor for development in regions where the ratio of demand to supply is 20 percent or higher. Basins where consumptive use exceeds 25 percent of average renewable supply, such as the Upper and Lower Colorado, California, Rio Grande, Great Basin, and Missouri, are particularly susceptible to further reductions in supply caused by climate change.

Neither of these measures captures more than a small part of the factors relevant for understanding a region's vulnerability to climate-induced changes in water supplies. Many water problems are local, and aggregating river basins into large water resource regions hides individual problem areas. A more fundamental shortcoming of these measures is that they do not take account of instream water uses (such as hydropower, fish and wildlife habitat, and recreation) that require large quantities of water and provide services of great importance to some areas, especially the Pacific Northwest.

Vulnerability to short- and long-term changes in water supplies also depends on how water is currently being consumed and the institutions in place to reallocate water when supplies are insufficient to meet all traditional uses. The more unused capacity or inefficiency there is in an existing system and the greater its ability to direct scarce supplies to higher value and more vulnerable users, the less susceptible to climatic conditions is the region as a whole. For instance, in times of shortage it would be much less costly and disruptive to curtail water use for irrigating lawns, pastures, and low-value annual crops than it would be to allow tree crops to perish, factories to close, or municipal water service to be rationed. With irrigation accounting for 90 percent of the consumptive use of water and with hay and pasture accounting for nearly one-third of irrigated acreage, it appears that there is at least the potential to have major reductions in water use at modest social costs in much of the West.

SUMMARY AND CONCLUSIONS

The quantity and quality of freshwater resources is of critical importance for both natural ecosystems and human development. Pressures on water resources are already rising due to population growth and industrial and commercial development. Any new threats to existing water resources must, therefore, be viewed with concern, especially where water is already limited in availability.

Water supply systems are naturally vulnerable to climatic variability and climate change. As a result, they are designed with a certain degree of resilience and robustness that permits them to operate over a wide range of conditions. When failures do occur, they are caused by unusually severe weather events or, occasionally, by the failure of system components to perform as designed.

Under some circumstances, climate change caused by the greenhouse effect will increase the risk of failure or the cost of maintaining or building facilities. In other cases, climate change will make changes in existing facilities imperative or will require new facilities. Lacking credible predictions of regional hydrologic changes, information about vulnerabilities and sensitivities can permit changes in design or operation in order to reduce the risk of failure.

The appropriate responses to permanent climate change are often different from those to short-term climatic variability. Unless long-term climate change can be distinguished from temporary variability, incorrect design and operation decisions could be made. A short drought, for instance, is often mitigated by surplus water from outside the basin or by temporary changes in water use. A long-term shortage, however, requires permanent changes in demand or changes in the physical infrastructure itself.

Of the various potential hydrologic consequences of climate change, one of the most difficult for most regions to handle would be increased variability, which translates into more frequent extremes--higher peak flood flows, more persistent and severe droughts, greater uncertainty about the timing of the rainy season. Few such changes would be beneficial. Changes in variability often prompt the most costly societal responses, such as flood control, large water transfers, and storage.

The existing infrastructure is generally both robust and resilient within the context of past hydrologic events, but its capacity for dealing with events that might result from a greenhouse warming is questionable. Uncertainties as to how climate change might alter regional supplies, as well as the high costs of building additional redundancy into water systems, increase the importance of nonstructural alternatives for coping with future scarcity and variability. These alternatives include improving the management of the existing infrastructure, encouraging conservation, marketing water to facilitate the movement of scarce supplies in response to changing supply and demand conditions, and developing and promoting technologies that increase the options for and decrease the costs of responding to changes in water supplies. Such measures not only may be needed but also may be more cost-effective approaches for coping with future hydrologic changes than would be developing major new facilities.

Institutional factors are often obstacles to realizing the potential of these alternatives. Multiple ownership and competing jurisdictions may stymie opportunities for integrated management of a region's water systems. Pricing policies of the urban water industry, subsidies for and restrictions on the use of federally supplied irrigation water, and state laws and administrative practices all discourage conservation. Federal and state laws and policies that obscure the nature of and reduce the transferability of water rights make water marketing unnecessarily difficult and expensive. Thus, incentives to develop and adopt water-conserving technologies on a timely basis are lacking.

There are no simple measures of a region's vulnerability to hydrologic events. The ratios of both storage and consumptive use to average renewable supply can be used to indicate whether or not a region is likely to be vulnerable to drought and flooding. However, these ratios alone do not incorporate such important considerations as instream water uses, the management of the water system, and the institutions that allocate and provide use incentives for scarce supplies. The flexibility to improve efficiency and allocate supplies to highly valued and vulnerable uses in response to adverse changes in water supply and demand will greatly reduce a region's vulnerability to the impacts of climate change on its hydrology.

REFERENCES

Bultot, F., A. Coppens, G. L. Dupriez, D. Gellens, and F. Meulenberghs. 1988. "Repercussions of a CO_2-Doubling on the Water Cycle and on the Water Balance: A Case Study for Belgium," *Journal of Hydrology*, in press.

Cohen, S. J. 1986. "Impacts of CO_2-Induced Climatic Change on Water Resources in the Great Lakes Basin," *Climatic Change 8*, pp. 135-154.

Flaschka, I. M., C. W. Stockton, and W. R. Boggess. 1987. "Climatic Variation and Surface Water Resources in the Great Basin Region," *Water Resources Bulletin 23*, pp. 47-57.

Frederick, Kenneth D. 1984. "Current Water Issues," *Journal of Soil and Water Conservation* vol. 39, no. 2.

_____. 1988. "The Future of Irrigated Agriculture," *Forum for Applied Research and Public Policy* vol. 3, no. 2.

_____, with James C. Hanson. 1982. *Water for Western Agriculture* (Washington, D.C., Resources for the Future).

Gibbons, Diana. 1986. *The Economic Value of Water* (Washington, D.C., Resources for the Future).

Gleick, P. H. 1986. "Methods for Evaluating the Regional Hydrologic Impacts of Global Climatic Changes," *Journal of Hydrology 88*, pp. 97-116.

_____. 1987. "Regional Hydrologic Consequences of Increases in Atmospheric CO_2 and Other Trace Gases," *Climatic Change 10*, pp. 137-161.

------. 1988a. "Regional Hydrologic Impacts of Global Climatic Changes," in E. E. Whitehead, C. F. Hutchinson, B. N. Timmermann, and R. G. Varady, eds., *Arid Lands: Today and Tomorrow*. Proceedings of an International Research and Development Conference, Tucson, Arizona, October 20-25, 1985 (Boulder, Colo., Westview/Belhaven Press).

_____. 1988b. "Climatic Changes and California: Past, Present, and Future Vulnerabilities" in M. Glantz, ed., *Societal Responses to Regional Climate Change: Forecasting by Analogy* (Boulder, Colo., Westview Press).

Hanchey, J. R., K. E. Schilling, and E. Z. Stakhiv. No date. "Water Resources Planning Under Climate Uncertainty" (unpublished paper, U.S. Army Institute for Water Resources, Fort Belvoir, Va., 22060).

Hardison, C. H. 1972. "Potential United States Water-Supply Development," in *Irrigation and Drainage Division Journal* vol. 98, pp. 479-492. Cited in U.S. Geological Survey (1984, p. 31).

Hayami, Yujiro, and Vernon W. Ruttan. 1985. *Agricultural Development: An International Perspective* (revised and expanded, Baltimore, Johns Hopkins University Press).

Hoffman, J. S. 1984. "Estimates of Future Sea Level Rise," in M. C. Barth and J. G. Titus, eds., *Greenhouse Effect and Sea-Level Rise* (New York, Van Nostrand Reinhold).

Langbein, W. B. 1959. "Water Yield and Reservoir Storage in the United States," U.S. Geological Survey Circular 409. Cited in U.S. Geological Survey (1984, p. 30).

Matalas, N. C., and M. B. Fiering. 1977. "Water-Resource Systems Planning," in National Research Council, *Climate, Climatic Change, and Water Supply* (Washington, D.C., U.S. National Academy of Sciences).

Nemec, J., and J. Schaake. 1982. "Sensitivity of Water Resource Systems to Climatic Variation," *Hydrological Sciences 17*, pp. 327-343.

Schlesinger, M. E. 1988. "Model Projections of the Climatic Changes Induced by Increased Atmospheric CO_2," in *Proceedings of the Symposium on Climate and Geosciences: A Challenge for Science and Society in the 21st Century* (Holland, Reidel Publishing, in press).

Sheer, Daniel P. 1986. "Managing Water Supplies to Increase Water Availability," in U.S. Geological Survey, *National Water Summary 1985--Hydrologic Events and Surface-Water Resources*, Water Supply Paper 2300 (Washington, D.C., Government Printing Office), pp. 101-112.

Shiklamanov, I. 1987. "Changes in Runoff in Soviet Rivers Due to Climate Change." Paper presented at the International Union of Geodesy and Geophysics Symposium, Vancouver, British Columbia, August 1987.

Solley, Wayne B., Charles F. Merk, and Robert R. Pierce. 1988. Estimated Use of Water in the United States in 1985, U.S. Geological Survey Circular 1004 (Washington, D.C., Government Printing Office).

Solley, Wayne B., Edith B. Chase, and William B. Mann IV. 1983. Estimated Use of Water in the United States in 1980, U.S. Geological Survey Circular 1001.

Szesztay, K. 1970. The Hydrosphere and the Human Environment: Results of Research on Representative and Experimental Basins, Proceedings, Wellington Symposium, UNESCO Studies and Reports in Hydrology, no. 12.

U.S. Department of the Interior, Bureau of Reclamation. 1987. Assessment '87... A New Direction for the Bureau of Reclamation (Washington, D.C.).

U.S. Geological Survey. 1984. National Water Summary 1983-Hydrologic Events and Issues, Supply Paper 2250 (Washington, D.C., Government Printing Office).

------. 1986. National Water Summary 1985-Hydrologic Events and Issues, Water Supply Paper 2300 (Washington, D.C., Government Printing Office).

U.S. Water Resources Council. 1978. The Nation's Water Resources: 1975-2000 vol. 2, Second National Water Assessment (Washington, D.C., Government Printing Office).

Vellinga, P. 1987. "Sea Level Rise, Consequences and Policies," background paper no. 9 for the Workshop on Developing Policies for Responding to Future Climatic Change, Villach, Austria, September 28-October 2, 1987.

Wahl, Richard W., and Robert K. Davis. 1986. "Satisfying Southern California's Thirst for Water: Efficient Alternatives," in Kenneth D. Frederick, ed., Scarce Water and Institutional Change (Washington, D.C., Resources for the Future), pp. 102-133.

Western Network. 1988. Water Market Update (Santa Fe, N.M.) published monthly since 1987.

World Meteorological Organization. 1988. Water Resources and Climatic Change: Sensitivity of Water-Resource Systems to Climate Change and Variability, World Climate Applications Program-4 (Geneva, Switzerland).

Table 10-1. Effect on Runoff of Climate Changes in Arid and Semiarid Basins

Basin/study	Temperature change (degrees C)	Precipitation change (percent)	Annual runoff change (percent)
Great Basin	+2	-10	-17 to -28
		+10	+20 to +35
Pease River	+3	-10	-50
		+10	+35
Sacramento	+2	-10	-18
		+10	+12

Note: For details on methods and model calculations refer to individual authors: Nemec and Schaake (1982) for the Pease River; Flaschka, Stockton, and Boggess (1987) for the Great Basin; and Gleick (1986, 1987) for the Sacramento.

Table 10-2. Decadal Reservoir Storage Capacity per Unit Volume of Dam for the 100 Largest Dams in the United States

Period	Index[a]
1920s or earlier	100.0
1930s	20.2
1940s	5.0
1950s	4.3
1960s	2.8

Source: Modified from Mermel (1958) as reported in U.S. Geological Survey (1984, p. 33).

[a] Index sets the average for the period of the 1920s and earlier at 100.0.

Table 10-3. Indicators of Vulnerability to Climatic Conditions

River basin or region	Measure of storage[a]	Measure of demand[b]
New England	.15	.01
Mid-Atlantic	.10	.02
South Atlantic-Gulf	.16	.03
Great Lakes	.08	.02
Ohio	.12	.02
Tennessee	.23	.01
Upper Mississippi	.14	.03
Lower Mississippi	.31	.09
Souris-Red-Rainy	.93	.07
Missouri	1.12	.29
Arkansas-White-Red	.45	.17
Texas-Gulf	.61	.23
Rio Grande	1.89	.64
Upper Colorado	2.61	.33
Lower Colorado	4.22	.96
Great Basin	.35	.49
Pacific Northwest	.19	.04
California	.42	.29
Alaska	.00	<.01
Hawaii	.01	.05
Caribbean	.05	.06

Source: U.S. Water Resources Council (1978) and U.S. Geological Survey (1986).

[a] Ratio of maximum basin storage volume to total basin annual mean renewable supply (1985). Regions with values below 0.6 have small relative reservoir storage volumes. Large reservoir storage volumes provide protection from floods and act as a buffer against shortages.

[b] Ratio of basin consumptive depletions (including consumptive use, water transfers, evaporation, and groundwater overdraft) to total basin annual mean renewable supply (1985). Water is considered a decisive factor for economic development in regions with values above 0.20 (Szesztay, 1970).

7 Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States

Roger R. Revelle and Paul E. Waggoner

In this chapter we show that warmer air temperatures and a slight decrease in precipitation would probably severely reduce both the quantity and the quality of water resources in the western United States. Similar effects can be expected in many water-short regions elsewhere in the world. We have not attempted to estimate these, primarily because we do not know enough to be able to do so. But we hope that hydrologists of other countries will be stimulated by our calculations to investigate the probable consequences of a CO_2-induced climate change on water resources in their own countries. In all countries, planning and construction of large-scale water-resource systems takes many decades. The time involved is of the same order of magnitude as the time over which a significant change in climate from increase of carbon dioxide and other greenhouse gases can be expected. Thus, we believe that planners and managers of water systems throughout the world should be able to make good use of forecasts of the hydrologic consequences of a warmer climate and of possible changes in precipitation.

7.1 EMPIRICAL RELATIONSHIPS AMONG PRECIPITATION, TEMPERATURE, AND STREAM RUNOFF

To assess the effects on the United States' water resources of probable climatic change we used the empirical relationship found by Langbein et al. (1949) among mean annual precipitation, temperature, and runoff. This was based on representative data from 22 drainage basins in the conterminous United States. Their relation in Table 7.1 gives the estimated annual runoff for different values of mean annual precipitations and weighted mean annual temperatures. The latter were computed for each catchment basin by dividing the sum of the products of average monthly temperature and precipitation by the mean annual precipitation. In this way, the average temperature during each month is weighted by the precipitation during that month.

The catchments studied by Langbein and his colleagues were distributed over climates from warm to cold and from humid to arid, but in Table 7.1 we have shown the relations among runoff, temperature, and precipitation only for relatively arid areas. In these arid areas, the value of actual evapotranspiration is less than the potential evapo-

TABLE 7.1 Runoff (mm yr^{-1}) as a Function of Precipitation and Temperature[a]

Weighted Average Temperature (°C)	Precipitation (mm yr-1) 200	300	400	500	600	700
- 2	54	92	154	230	330	440
0	40	74	124	190	275	380
2	28	57	95	154	225	320
4	17	40	78	125	190	265
6	9	25	60	100	155	220
8	0	17	42	82	128	185
10		8	29	64	103	155
12		0	19	47	80	130
14			10	32	65	105
16			0	20	50	85

[a] Source: W. B. Langbein et al. (1949).

transpiration that would occur if sufficient water were present and evapotranspiration was controlled mainly by temperature. For example, at a temperature of 4°C, potential evapotranspiration is about 450 mm yr^{-1}. Yet Langbein's data show that even when annual precipitation is only 300 mm, there is still significant runoff, about 13% of the precipitation. Correspondingly, average actual evapotranspiration must be only 260 mm yr^{-1}.

From Table 7.1 we observe that for any given annual precipitation, runoff diminishes rapidly with increasing temperature. Similarly, for any given temperature, the proportion of runoff to precipitation increases rapidly with increasing precipitation. For example, at a weighted mean annual temperature of 4°C and annual precipitation of 200 mm, runoff is only 8.5% of precipitation, whereas for the same temperature and an annual precipitation of 700 mm, runoff is 38% of precipitation. At an annual temperature of 8°C, runoff is zero when precipitation is 200 mm or less and is 185 mm--or 26.4% of precipitation--when the average annual precipitation is 700 mm.

For any particular region, the relations shown in Table 7.1 are rather crude approximations because many physical factors, including geology, topography, size of drainage basin, and vegetation, may alter the effect of climate on runoff. We believe, nevertheless, that these relationships can be used without serious error to describe the effects of relatively small changes in average temperature and precipitation on mean annual runoff.

In Table 7.2, we have used the data in Table 7.1 to compute the approximate percentage decrease in runoff for a 2°C increase in temperature. Climate models (e.g., Manabe and Wetherald, 1980) indicate that a temperature change of this magnitude or greater is likely as a result of the doubling of carbon dioxide and increased concentration of "greenhouse gases" expected during the next century. We see that for a

TABLE 7.2 Approximate Percent Decrease in Runoff for a 2°C Increase in Temperature[a]

Initial Temperature (°C)	Precipitation (mm yr-1) 200	300	400	500	600	700
- 2	26	20	19	17	17	14
0	30	23	23	19	17	16
2	39	30	24	19	17	16
4	47	35	25	20	17	16
6	100	35	30	21	17	16
8		53	31	22	20	16
10		100	34	22	22	16
12			47	32	22	19
14			100	38	23	19

[a] Computed from Table 7.1.

present weighted mean annual temperature of 4°C and annual precipitation of 300 mm, a 35% diminution in runoff would follow a 2°C warming. The percentage decrease in runoff from a warming diminishes with increasing precipitation and becomes greater for successively higher values of the initial temperature.

Table 7.3 shows the approximate percentage decreases in runoff for a 10% decrease in precipitation. According to the results of climate models (see Chapter 4), such a diminution in precipitation is likely, at least in certain regions of the United States, with a doubling of atmospheric CO_2. Again we see that the effect becomes larger with higher average annual temperatures. There is a relatively small difference in the percentage decrease in runoff at a given temperature over the range of initial precipitation values shown in the table. Comparison of Tables 7.2 and 7.3 shows that below an initial mean annual precipitation of 500 mm, the effects of a 2°C warming are larger than those caused by a 10% decrease in precipitation. The reverse is true when mean annual precipitation is 500 mm or more.

7.2 EFFECTS OF CLIMATE CHANGE IN SEVEN WESTERN U.S. WATER REGIONS

Stockton and Boggess (1979) have used Langbein's empirical relation to estimate the effects of a climatic change on water in the 18 water regions of the conterminous United States defined by the U.S. Water Resources Council (1978). They find that a 2°C warming and a 10% reduction in precipitation would not have serious effects in the humid regions east of the 100th meridian. In the West, however, the impact would be severe on seven water regions: the drainage basins of the Missouri, Arkansas-White-Red, Rio Grande, and Colorado rivers; the river basins draining into the Gulf of Mexico from the northern two thirds of Texas; and the rivers of California. The only western water

TABLE 7.3 Approximate Percentage Decrease in Runoff for a 10% Decrease in Precipitation[a]

Temperature (°C)	Initial Precipitation (mm yr-1)				
	300	400	500	600	700
- 2	12	16	17	18	18
0	14	16	17	19	19
2	15	16	19	19	20
4	17	19	19	21	21
6	23	23	21	21	21
8	30	24	24	22	22
10		24	27	23	23
12		40	30	25	25
14			34	30	27
16			50	36	29

[a] Computed from Table 7.1.

regions that would not be severely affected are the water-rich Pacific Northwest and the Great Basin (parts of Nevada, Utah, and Idaho), where demand is relatively small and groundwater reserves are large.

In estimating the impact of climate change, Stockton and Boggess assumed:

1. The region-by-region variation in annual runoff is predominantly influenced by climate, although other factors such as geology, topography, vegetation, and many other variables may be important, especially in smaller drainages.
2. The empirical curves associating total annual precipitation and total annual runoff with weighted mean annual temperature are appropriate for all 18 regions although derived from a relatively small (22 drainage basin) sample.
3. Changes in land use have relatively small influences on regionwide annual runoff.
4. Annual runoff is not greatly affected by large-scale groundwater overdraft.
5. Evapotranspiration is controlled solely by temperature.
6. The postulated climatic change does not modify the present monthly distribution of temperature and precipitation; only the amplitude of the present distribution is increased or decreased.
7. Selection of a few meteorological stations for each region adequately establishes the relation of the weighted mean temperature and annual precipitation to annual runoff.

In Table 7.4 we have summarized the estimates by Stockton and Boggess of the effects of a 2°C increase in temperature and a 10% reduction in precipitation in the seven water regions of the western United States in which climate change would have the most serious

TABLE 7.4 Comparison of Water Requirements and Supplies for Present Climatic State and for a 2°C Increase in Temperature and 10% Reduction in Precipitation in Seven Western U.S. Water Regions[a]

	Present Climate						Warmer and Drier Climate		
Water Region[b]	Area ($10^{10}/m^2$)	Mean Annual Runoff (10^{10} m^3 yr^{-1})	(mm)	Mean Annual Supply (10^{10} m^3 yr^{-1})	Mean Annual Requirements[c] (10^{10} m^3 yr^{-1})	Ratio of Requirement to Supply	Mean Annual Supply (10^{10} m^3 yr^{-1})	Percent Change in Supply	Ratio of Requirement[d] to Supply
Missouri	132.4	8.50	64	8.50	3.63	0.43	3.07	-63.9	1.18
Arkansas-White-Red	63.2	9.35	148	9.35	1.67	0.18	4.32	-53.8	0.39
Texas Gulf	44.9	4.92	110	4.92	1.74	0.35	2.47	-49.8	0.70
Rio Grande	35.2	0.74	21	0.74	0.67	0.91	0.18	-75.7	3.72
Upper Colorado	29.6	1.64[e]	55	1.64	1.63[f]	0.99	0.99	-39.6	1.65
Lower Colorado	40.1	0.38	10	1.15[g]	1.37	1.19	0.50[g]	-56.5	2.68
California	42.9	9.56	222	10.18[g]	4.22	0.41	5.71[g]	-43.9	0.74
For the 7 regions together	388.3	35.09	90.4	35.09[h]	14.93	0.43	16.53[h]	-53	0.90

[a] Source: Stockton and Boggess (1979) and calculations in this paper for Upper Colorado Basin.

[b] As defined by the U.S. Water Resources Council (1978).

[c] Projected through year 2000 A.D.

[d] Assuming no increase in requirement because of increased evapotranspiration from irrigated farms or reservoirs.

[e] Average "virgin flow" of the Colorado River at Lee Ferry from 1931 to 1976.

[f] Includes allocation to Lower Basin States, California included, of 0.93×10^{10} m^3 yr^{-1}.

[g] Includes water received from Upper Colorado Basin, but not mined groundwater.

[h] Total is less than sum of the column because of flow of Lower Colorado derived from Upper Colorado (g).

impact. These regions cover about half the area of the conterminous United States, but they produce only about 15% of the mean annual stream runoff. The table shows the present mean annual water supply for each region, not including mined groundwater, in millions of hectare meters (10^{10} m^3 yr^{-1}) and the estimated mean annual requirement in the year 2000. The mean annual requirements listed in Table 7.4 represent "consumptive" use of water plus evaporation from reservoirs, that is, the total quantity of water that is evapotranspired in the course of beneficial human use. Although actual withdrawals from streams and underground aquifers are considerably larger, portions of these withdrawals are returned to the streams or back into the ground where the water may be reused. In the present climate the ratio of estimated requirements to supplies is less than one for all regions except the Lower Colorado River. In this region today, the deficit of supply is presently made up by extensive mining of groundwater.

For the postulated climatic change, supplies would greatly diminish in all regions, ranging from almost a 76% reduction in the Rio Grande region to nearly 40% in the Upper Colorado, with the result that estimated requirements would exceed supplies in the Missouri, Rio Grande, and Upper and Lower Colorado regions. Mean annual requirements would still be less than future mean annual supplies in the Arkansas-White-Red, Texas Gulf, and California regions. But requirements would almost certainly exceed supplies in the Texas Gulf and California regions during future prolonged droughts. Conditions are highly variable in different parts of the Arkansas-White-Red region, with the western part tending to be deficient in water supplies and the eastern part having a surplus. To maintain the present pattern of water use, large-scale transfers between basins might be necessary here even under average conditions, let alone to meet water requirements during prolonged droughts. A serious deterioration in water quality would follow from climatic change in all seven regions.

The ratio of future requirements to supply would probably be even less favorable than indicated in Table 7.4 because evapotranspiration from irrigated farms and reservoirs would undoubtedly increase with a rise in temperature. On a global basis this would be compensated for by an increase in precipitation, but this might or might not occur in the regions we are considering.

At present, California depends for about 15% of its water on imports from the Colorado River. These imports might be eliminated entirely with the postulated climatic change, in which case the ratio of mean annual requirements to mean annual runoff would increase to 0.83, more than double the present ratio.

In all seven regions, irrigation is by far the largest user. Its share of water withdrawals ranges from 68% in the Texas Gulf region to 95% in the Rio Grande region. Total water withdrawals for agriculture are now 13.2 million hectare meters, and in the seven regions the irrigated area is (very approximately) 13 million hectares (Rogers, 1983) so that, on the average, the annual depth of irrigation is about 1 m. Consumptive water use in irrigation is much smaller; a large share of the water that is not consumed reappears as return flows that can be used downstream. Reduction in the irrigated area and an increase in the efficiency of water use in irrigation would significantly lower the overall water requirements in the seven western regions. A 15% increase in water-use efficiency is probably feasible (Jensen, 1982). Reduction in the irrigated area might come about automatically if an interstate economic market for water were to develop, because economic returns to irrigation are relatively low in large parts of the seven western regions. On the other hand, potentially very large Indian claims for irrigation water for their reserved lands must eventually be settled, and this could result in a major reallocation of water rights (Back and Taylor, 1980).

The effects of future droughts in the Arkansas-White-Red, Texas Gulf, and California regions from the assumed climatic change could be significantly mitigated by construction of additional reservoirs for water storage, but increases in storage would help little in the Missouri, Rio Grande, or Upper and Lower Colorado regions because their storage reservoirs are already so large compared to the annual runoff. In these regions strict water conservation would be essential.

The mean annual requirements listed in Table 7.4 represent "consumptive" use of water plus evaporation from reservoirs, that is, the total quantity of water that is evapotranspired in the course of beneficial human use. Although actual withdrawals from streams and underground aquifers are considerably larger, portions of these withdrawals are returned to the streams or back into the ground where the water may be reused.

As Stockton and Boggess show, the one western region where a large surplus would still exist after their postulated climatic change would be the Pacific Northwest. Their estimated ratio of requirements to supplies following a 2°C warming and a 10% reduction in precipitation would be 0.10. The annual supply would then be 23.7 million hectare meters. Transfer of 20% of this total supply to water-short regions through large, long-distance conveyance could increase future supplies in the seven western regions shown in Table 7.4 by nearly 30%, thereby compensating for much of the estimated shortages from climatic change. The ratio of requirements to supplies in the Pacific Northwest region would still be a comfortable 0.18.

From an economic standpoint, however, such a transfer would probably not be desirable. The value of the hydroelectric energy that could be generated from a hectare meter of water in the Pacific Northwest, assuming a total head of 500 m and a price of 5¢ per kilowatt-hour, would be over $600, considerably in excess of the value of a hectare meter of water for irrigating the fodder and cereal crops grown in most of the western regions (Rogers, 1983).

7.3 THE COLORADO RIVER

Except for the Rio Grande, the waters of the Colorado River are more intensively used than those of any other major stream in the United States. Half the estimated "normal" flow of 18,500 million cubic meters per year at Lee Ferry in Arizona has been allocated by interstate compact, confirmed by federal law, to the lower basin states of California and Arizona, with minor amounts going to Nevada. Nearly all of the runoff originates from snow in the high-mountain area of western Colorado, southwestern Wyoming, and eastern Utah.* (As defined, the Upper Basin also includes northwestern New Mexico.)

To check the probable effect of a climatic change on the flow of the Colorado River, we calculated a multiple regression of the relation between annual averages of precipitation and temperature and the "virgin flow" of the Colorado at Lee Ferry, Arizona, which is the southernmost point on the river in the Upper Colorado Basin.

The "virgin flow" is the measured flow at Lee Ferry plus estimated depletions within the upper basin, evaporation from reservoirs, and changes in reservoir storage. Estimates for the annual virgin flows were furnished to us by Myron B. Holbert, chief engineer of the Colorado River Board of California. The flow for each water year--October 1 to September 30--from 1931 to 1976 is tabulated in Table 7.5. It ranges from 9,450 to 25,490 million cubic meters. The average for the 46-year period is 16,430 million cubic meters (13.5 million acre feet). This average value is 2065 million cubic meters, or 11% less than the assumed "normal flow" on which the Colorado River Compact is based, but it agrees well with Langbein's relationship, shown in Table 7.1, among temperature, precipitation, and runoff. Interpolating between the values given in the table for temperatures of 4 and 6°C and precipitation of 300 and 400 mm yr^{-1}, we arrive at a runoff of 53 mm, corresponding to an annual river flow for the 296,000 km^2 in the Upper Colorado drainage of 15,700 million m^3.

The flow of the Colorado is mainly collected in five catchments corresponding to the five climatic divisions in the Upper Colorado Basin outlined in Figure 7.1. Mean annual precipitation and temperature for each drainage area and water-year from 1931 to 1976 were provided to us by Daniel Cayan of the Scripps Institution of Oceanography, who obtained the original data from the National Climate Center, Asheville, North Carolina. The annual data for each division are the areally weighted averages of the records of individual weather stations. As Cayan has pointed out, the number of weather stations was not constant but gradually increased from 1931 to 1976. Between 1951 and 1980, continuous records were obtained from 45 stations in the western Colorado division, 10 stations in the Green and Bear drainages in Wyoming, and 10 in the three drainage basins of eastern Utah (North Mountains, Uinta Basin, and Southeast Utah). By 1980, there were 65 stations in western Colorado, 26 in the three Utah divisions, and 16 in southwestern Wyoming.

We weighted the data from these five drainage basins in proportion to their areas: Colorado drainage in western Colorado, 0.430; Green and Bear drainages in Wyoming, 0.184; North Mountains in Utah, 0.110;

---

*See Dracup (1977) and Howe and Murphy (1981) for useful discussions of the economic, social, political, and international problems of the Colorado River compact.

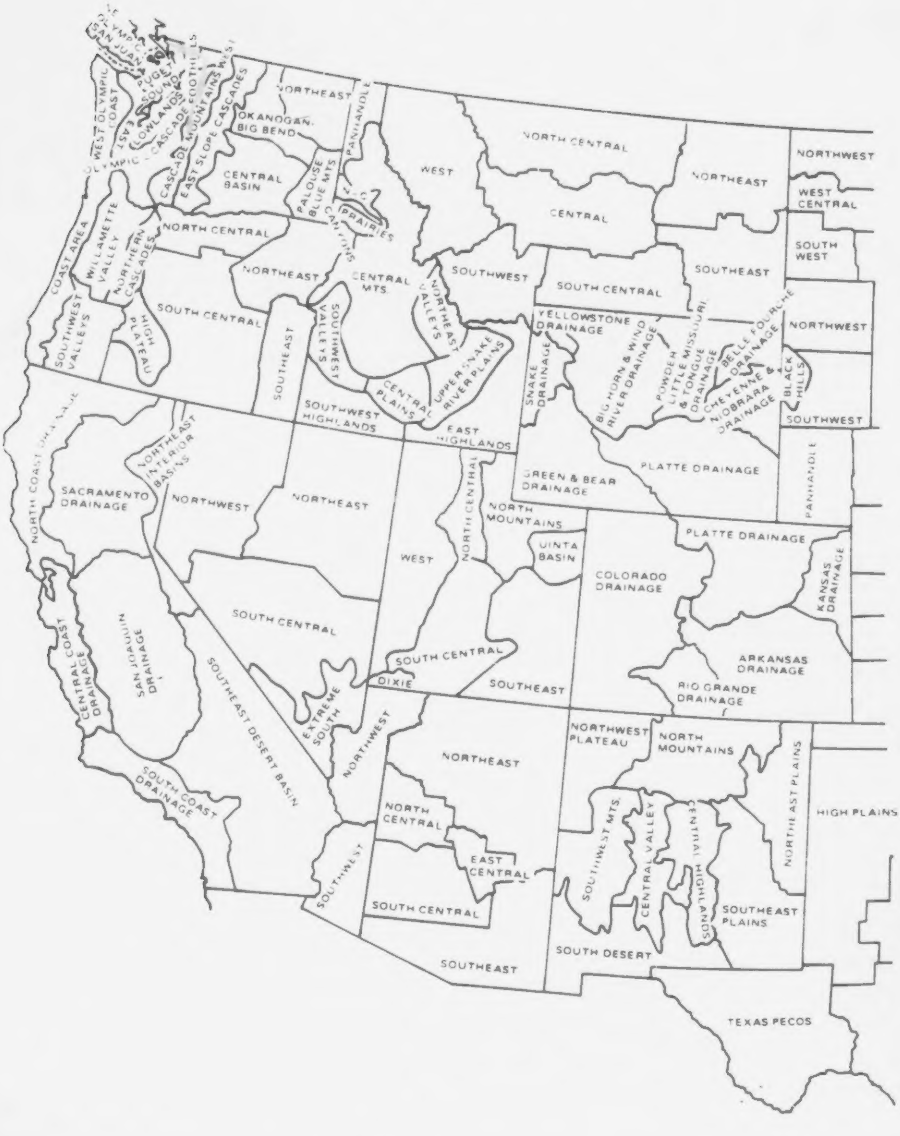

OLYMPIC
SAN JUAN
WEST OLYMPIC COAST
EAST OLYMPIC
PUGET SOUND LOWLANDS
CASCADE FOOTHILLS
CASCADE MOUNTAINS WEST
CASCADE
EAST SLOPE CASCADES
NORTHEAST
OKANOGAN-BIG BEND
PANHANDLE
CENTRAL BASIN
PALOUSE BLUE MTS
CANYONS
PRAIRIES
NORTH CENTRAL
WEST
NORTH CENTRAL
NORTHEAST
NORTHWEST
WEST CENTRAL
CENTRAL
SOUTH WEST
SOUTHWEST
SOUTH CENTRAL
SOUTHEAST
NORTHWEST
COAST AREA
WILLAMETTE VALLEY
NORTHERN CASCADES
NORTHEAST
CENTRAL MTS.
NORTHEAST VALLEYS
SOUTH CENTRAL
HIGH PLATEAU
SOUTHWEST VALLEYS
SOUTHEAST
SOUTHWEST VALLEYS
CENTRAL PLAINS
UPPER SNAKE RIVER PLAINS
SOUTHWEST HIGHLANDS
EAST HIGHLANDS
YELLOWSTONE DRAINAGE
SNAKE DRAINAGE
BIG HORN & WIND RIVER DRAINAGE
POWDER LITTLE MISSOURI & TONGUE DRAINAGE
BELLE FOURCHE DRAINAGE
CHEYENNE & NIOBRARA DRAINAGE
BLACK HILLS
SOUTHWEST
NORTH COAST DRAINAGE
NORTHEAST INTERIOR BASINS
SACRAMENTO DRAINAGE
NORTHWEST
NORTHEAST
WEST
NORTH CENTRAL
NORTH MOUNTAINS
GREEN & BEAR DRAINAGE
PLATTE DRAINAGE
PANHANDLE
UINTA BASIN
COLORADO DRAINAGE
PLATTE DRAINAGE
KANSAS DRAINAGE
SOUTH CENTRAL
SAN JOAQUIN DRAINAGE
CENTRAL COAST DRAINAGE
SOUTHEAST DESERT BASIN
SOUTH CENTRAL
DIXIE
SOUTHEAST
EXTREME SOUTH
ARKANSAS DRAINAGE
RIO GRANDE DRAINAGE
NORTHWEST
NORTHEAST
NORTHWEST PLATEAU
NORTH MOUNTAINS
NORTHEAST PLAINS
HIGH PLAINS
SOUTH COAST DRAINAGE
NORTH CENTRAL
EAST CENTRAL
SOUTHWEST
SOUTH CENTRAL
SOUTHEAST
SOUTHWEST MTS.
CENTRAL VALLEY
CENTRAL HIGHLANDS
SOUTHEAST PLAINS
SOUTH DESERT
TEXAS PECOS

FIGURE 7.1 Basins or drainages of the western United States.

Uinta Basin, 0.053; and southeast Utah, 0.223. The weighted sum of the precipitation in millimeters for the five drainages is called PRECIP in the following equation. It varies from 262 to 439 mm yr^{-1}, with an average for the 46 years of 332 mm yr^{-1}. Weighted annual average temperatures obtained in the same manner are called CELSIUS. They range from 2.52 to 6.75°C and average 4.18°C. The weighted annual averages for 1931 to 1976 are tabulated in Table 7.5.

The relation of the virgin flow to PRECIP and CELSIUS is assumed to fit the equation:

$$\text{FLOW} = b_0 + (b_1 \times \text{PRECIP}) + (b_2 \times \text{CELSIUS}).$$

The regression coefficients, b_i, and their standard errors relating the virgin flow at Lee Ferry to the mean annual precipitation and the mean annual temperature in the watershed from 1931 to 1976 are as follows:

b_0 in millions of cubic meters = 9274 ± 3838,
b_1 in millions of cubic meters/mm = 52 ± 7,
b_2 in millions of cubic meters/°C = -2400 ± 507.

The fit of the equations to the data is represented by the square of the correlation coefficient, R^2, which is 0.73. About 75% of the variation of the flow about the mean is explained by the equations.

We see that a 2°C rise in temperature would decrease the virgin flow by 4800 ± 1015 million cubic meters yr^{-1}, or about 29% ± 6%. A 10% decrease in precipitation would reduce the flow by 1730 ± 230 cubic meters, or an additional 11% ± 1.4%. The combined effect would be a reduction in flow by 40% ± 7.4%, very close to the estimate of 44% given by Stockton and Boggess.

Estimates of the virgin flow between 1900 and 1930 were also provided by Holbert, and we attempted a similar analysis for these years, using data published in the Weather Bureau publication, The Climates of the States. Unfortunately, the data for these earlier years are sparse. Only 10 stations recorded precipitation more or less continuously during this period in western Colorado and even fewer in Utah and Wyoming. Temperature data were available from only Garnett, Colorado; Lander, Wyoming; and Modena, Utah, and none of these is in the high-mountain regions of heavy snowpack that contribute most of the runoff to the Colorado River.

The data for 1900 to 1930, Table 7.6, indicate that the average runoff was about 20% greater than between 1931 and 1976, while the average precipitation was about 7% less and the average temperatures for the three available stations were about 2°C higher. The low estimate of average precipitation may reflect a deficiency in estimating the quantities of water precipitated as snow. These estimates were very uncertain before the advent of the "snow courses" initiated by the U.S. Soil Conservation Service in the 1930s. The extreme variations in average annual temperature for the three stations were only 2.45°C, in contrast to the range of 4.23°C for the average of the much larger number of stations in 1931-1976.

TABLE 7.5 Annual Averages of Precipitation, Temperature, and Virgin Flow of the Colorado River at Lee Ferry, Upper Colorado Region, 1931-1976

Year	Precipitation (mm yr^{-1})	Temperature (°C)	Flow (10^6 m^3 yr^{-1})
1931	268	4.95	9583
1932	355	3.23	21270
1933	283	3.51	14009
1934	228	6.75	6958
1935	316	5.14	14247
1936	349	4.62	17023
1937	378	3.80	16948
1938	392	5.04	21643
1939	301	4.22	13666
1940	323	5.71	10609
1941	451	4.11	22386
1942	357	3.51	23592
1943	362	4.68	16164
1944	334	3.99	18693
1945	355	3.97	16542
1946	305	4.08	12860
1947	418	4.39	19083
1948	346	4.13	19258
1949	385	3.32	20199
1950	320	3.68	15904
1951	298	4.60	14366
1952	424	3.20	25490
1953	273	4.63	13119
1954	308	5.64	9450
1955	291	3.57	11333
1956	255	4.31	13259
1957	429	4.25	24787
1958	323	4.28	20339
1959	294	4.75	10619
1960	262	4.49	13893
1961	340	4.82	10432
1962	300	3.38	21338
1963	305	5.44	10423
1964	286	3.61	12527
1965	439	3.30	23329
1966	282	4.06	13825
1967	350	4.20	14687
1968	326	3.45	16854
1969	361	3.84	17745
1970	352	4.05	19002
1971	302	3.78	18645
1972	303	3.46	15021
1973	435	2.52	23893
1974	254	4.22	16355
1975	347	3.51	20447
1976	300	4.27	14064
Mean	333	4.18	16432

TABLE 7.6 Annual Averages of Precipitation, Temperature, and Virgin Flow of the Colorado River at Lee Ferry, Upper Colorado Region, 1901-1930

Year	Precipitation (mm yr^{-1})	Temperature (°C)	Annual Sum (m/sec)
1901	229	6.56	16753
1902	195	6.71	11586
1903	285	5.35	18264
1904	240	6.55	19297
1905	314	6.10	19769
1906	370	5.86	23585
1907	350	6.78	28865
1908	274	6.49	15857
1909	364	6.05	28709
1910	233	6.57	17574
1911	327	7.49	19770
1912	313	5.05	25311
1913	269	5.71	17852
1914	355	6.68	26176
1915	308	6.47	17303
1916	304	7.08	23684
1917	346	5.04	29650
1918	263	7.32	18951
1919	253	6.43	15372
1920	331	5.58	27076
1921	355	6.57	28389
1922	300	6.60	22580
1923	336	6.04	22535
1924	252	5.63	17517
1925	338	6.41	16077
1926	303	6.28	19554
1927	404	6.88	22963
1928	253	6.58	21314
1929	392	5.46	26432
1930	309	6.44	18361
Mean	306	6.29	21098

The multiple regression for the earlier period showed a smaller effect of temperature and a somewhat larger effect of precipitation than during 1931-1976. But during the earlier period the standard deviations for the effects of both temperature and precipitation were almost twice as great, and the square of the correlation coefficient was only 0.57.

We conclude tentatively that the weakness of the correlation and the relatively larger standard errors from 1901 to 1930 resulted from the paucity of precipitation and temperature data, the probable inaccuracy of estimates of the quantity of water precipitated as snow, and the probably unrepresentative character of the stations used for average temperatures. In both the earlier and the later periods, variations in precipitation were reflected almost linearly in variations in runoff without the amplification that might be expected from the results obtained on smaller watersheds (Schaake and Kaczmarek, 1979) or from Table 7.3.

After the postulated climatic change, the mean annual flows at Lee Ferry computed from our multiple regression equation for 1931 to 1976 would be only 9900 million cubic meters. This last amount is 2060 million cubic meters, or 17%, less than the historically lowest 10-year average annual flow of 11,960 million cubic meters, calculated by Stockton from tree-ring records for the decade from A.D. 1584 to A.D. 1593 (Dracup, 1977). A similar prolonged drought in the middle of the twenty-first century with the same percentage decrease in runoff as in 1584-1593 could bring the 10-year annual average flow down to 7200 million cubic meters, or about 44% of the annual average virgin flow from 1931 to 1976.

Although a 2°C warming is probably a conservative estimate of the effect over the next hundred years of increase of greenhouse gases for the northern United States, the magnitude and even the sign of possible changes in precipitation are uncertain. According to our regression equation, a 10% increase in average annual precipitation combined with a 2°C rise in average temperature would result in an 18% decrease in runoff. To counteract the effects of a 2°C warming completely, a 28% increase in precipitation would be required. Clearly, higher spatial resolution in climate models is needed for more credible forecasts of the effects of increasing atmospheric carbon dioxide and other greenhouse gases on the quantity of water supplies. Possibly, also, seasonal variations from year to year in precipitation and temperature may be more critical in determining Colorado River runoff than annual averaged variations. This possibility could be investigated by statistical analysis of monthly averages of temperature and precipitation for each year against the annual "virgin flow" at Lee Ferry.

7.4 CLIMATE CHANGE AND WATER-RESOURCE SYSTEMS

Planning and construction of major water-resource systems have a time constant of 30 to 50 years. In the past, these activities have been based on the explicit assumption of unchanging climate. The probably serious economic and social consequences of a carbon dioxide-induced climatic change within the next 50 to 100 years warrant careful consideration by planners of ways to create more robust and resilient water-resource systems that will, insofar as possible, mitigate these effects.

REFERENCES

Back, W. D., and J. S. Taylor (1980). Navajo water rights: pulling the plug on the Colorado River. Natural Resources Journal, January 1980, pp. 70-90.

Dracup, J. A. (1977). Impact on the Colorado River Basin and Southwest water supply. In Climate, Climatic Change, and Water Supply. National Academy of Sciences, National Academy Press, Washington, D.C.

Howe, C. W., and A. H. Murphy (1981). The utilization and impacts of climate information on the development and operations of the Colorado River system. In Managing Climatic Resources and Risks. Panel on the Effective Use of Climate Information in Decision Making, Climate Board, National Academy of Sciences, Washington, D.C., pp. 36-44.

Jensen, M. E. (1982). Water resources technology and management. Paper presented at Soil and Water Resources Conservation Act Symposium on Future Agricultural Technology and Resource Conservation, December 1982.

Laney, N. (1982). Does Arizona's 1980 Groundwater Management Act violate the Commerce Clause? Arizona Law Review 24:108-131.

Langbein, W. B., et al. (1949). Annual Runoff in the United States. U.S. Geological Survey Circular 5. U.S. Dept. of the Interior, Washington, D.C. (reprinted, 1959).

Manabe, S., and R. T. Wetherald (1980). On the horizontal distribution of climate change resulting from an increase of CO_2 content of the atmosphere. J. Atmos. Sci. 37:99-118.

Rogers, P. (1983). Water resource technology and management in the future of U.S. agriculture. Paper presented at the Soil and Water Resources Conservation Act Symposium on Future Agricultural Technology and Resource Conservation, December 1982.

Schaake, Jr., J. S., and Z. Kaczmarek (1979). Climate variability and the design and operation of water resource systems. In Proceedings of the World Climate Conference, pp. 290-312. World Meteorological Organization, Geneva, Switzerland.

Stockton, C. W., and W. R. Boggess (1979). Geohydrological implications of climate change on water resource development. U.S. Army Coastal Engineering Research Center, Fort Belvoir, Virginia.

U.S. Water Resources Council (1978). The Nation's Water Resources, The Second National Water Assessment. U.S. Govt. Printing Office, Washington, D.C.

Water Resources Planning Under Climate Uncertainty

J.R. Hanchey[1], K.E. Schilling[2] and E.Z. Stakhiv[3]
U.S. Army Institute for Water Resources
Fort Belvoir, VA 22060

ABSTRACT

Hydrologic risks and uncertainties related to climate and water resources project planning are dealt with from the perspective of an operating agency and its relevant missions, responsibilities and constraints. Although the prognosis that climate changes are likely to occur from CO_2 - induced warming is accepted by Corps scientists and engineers, this knowledge can not be directly factored into planning and design procedures at the present time. There are several indirect paths however, through which likely climate change consequences are implicitly taken into account in planning and design.

In addition, there are realistic expectations that a substantial social adaptation would occur to further ameliorate some of the emerging adverse consequences. The Corps' typical planning horizon is for a fifty year project life. Thus the Corps should be cognizant of significant expected changes in that time frame. However, certain economic decision rules and a fiscal discount rate truncate project evaluation and decision making to about 12 years. On the other hand, the Corps' pragmatic engineering approach to project design relies on historical weather extremes and runoff that has fluctuated from the cold epoch of the late 19th century to a very dry and warm period in the 1930's and 1940's. Together, these two fundamental decision criteria (hydrology and economics) have resulted in projects that are both economically efficient and that are robust and resilient in their performance under reasonably foreseeable climate uncertainty.

The Corps-developed water resources infrastructure, along with that of other federal and publicly owned water agencies, constitutes an immense system that allows for a substantial degree of operating flexibility in many, but not all the river basins of the coterminous United States. Improved management of this system, reallocation of water supply, greater marketing of water rights will provide many areas in the U.S. a valuable margin of safety, during the time in which we strive to better understand the precise nature of climate-hydrology interactions. The Corps is taking steps to address the changes in several separate but ultimately converging research and study efforts, especially to tie risk and engineering

---

[1] Director.

[2] Chief, Policy Studies Division.

[3] Program Manager, Research Division.

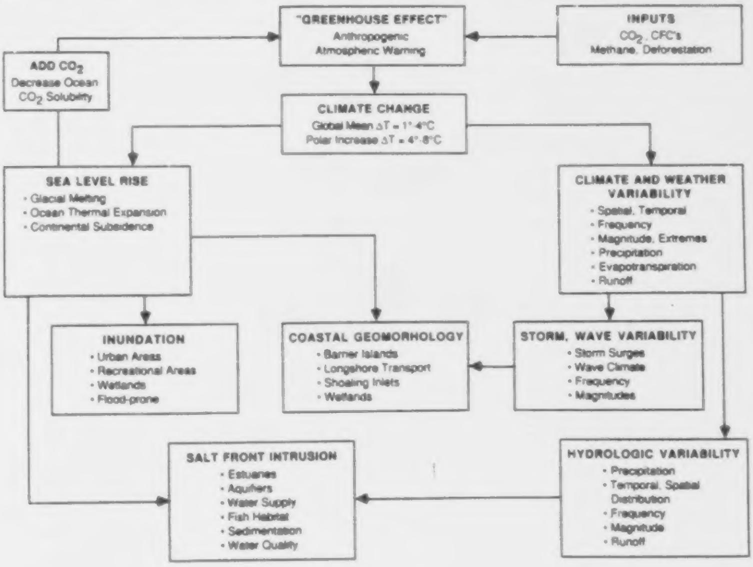
reliability analysis with benefit cost analysis. Risk and uncertainty analysis in project planning will encompass climate uncertainty and its effect on the choices of alternative solutions and their proper scale. More effort will go into the development of hydrologic tools and procedures for dealing with climate uncertainty.

INTRODUCTION

The U.S. Army Corps of Engineers, is responsible for various aspects of a diverse water resources and coastal shoreline protection program. The Corps recognizes that their activities are likely to be affected by the hydrologic, meteorologic, and oceanographic consequences of global warming and expected climate changes (Figure 1). While the Corps may appear to be relatively unresponsive to are increasingly important hazard, it has been delving into the ramifications of these changes for some time now. Most of the Corps' incremental modifications so far have dealt with its planning and design procedures which address the manner in which the Corps computes physical (hydrologic and hydraulic) changes and forecasts economic conditions. A primary change has been in the explicit introduction of risk analysis for the selection of an appropriate design basis for the various alternative plans and corrponent projects whose purposes are to ameliorate hydrologic extremes and mitigate their social and economic consequences.

FIGURE 1

PHYSICAL CONSEQUENCES OF CLIMATE CHANGE


"GREENHOUSE EFFECT"
Anthropogenic
Atmospheric Warming
INPUTS
CO_2, CFC's
Methane, Deforestation
ADD CO_2
Decrease Ocean
CO_2 Solubility
CLIMATE CHANGE
Global Mean ΔT = 1°-4°C
Polar Increase ΔT = 4°-8°C
SEA LEVEL RISE
• Glacial Melting
• Ocean Thermal Expansion
• Continental Subsidence
CLIMATE AND WEATHER VARIABILITY
• Spatial, Temporal
• Frequency
• Magnitude, Extremes
• Precipitation
• Evapotranspiration
• Runoff
INUNDATION
• Urban Areas
• Recreational Areas
• Wetlands
• Flood-prone
COASTAL GEOMORHOLOGY
• Barrier Islands
• Longshore Transport
• Shoaling Inlets
• Wetlands
STORM, WAVE VARIABILITY
• Storm Surges
• Wave Climate
• Frequency
• Magnitudes
SALT FRONT INTRUSION
• Estuaries
• Aquifers
• Water Supply
• Fish Habitat
• Sedimentation
• Water Quality
HYDROLOGIC VARIABILITY
• Precipitation
• Temporal, Spatial Distribution
• Frequency
• Magnitude
• Runoff

Currently, the Corps is focusing on the relatively uncertain intra-continental effects of climate change on water resources projects. It is recognized that coastal effects, being more certain (at least in the direction of change, if not magnitude) will allow earlier direct response by the Corps and other responsible institutions. It is also recognized that innovative management of existing projects is as important as planning for new projects, perhaps more so because fewer large scale new multipurpose projects are likely to be built in the future. Finally, construction of structural modifications alone is not the only answer. A more complete discussion, beyond the scope of this paper, requires explicit recognition of strategies to prevent or slow the factors that contribute to climate change(e.g. production of carbon dioxide and chlorofluorocarbons); prevent damages from climate change by limiting damageable development or use of resources likely to become scarce; and, for compensation of lost property or abandonment of threatened property (e.g. floodplains, barrier beaches.)

As yet, the Corps has not developed a focused and direct policy statement that emphasizes the importance of considering climate change either for existing water resources management projects or for the planning and design of new ones. Part of the reason resides in the comforting notion that many of the engineering profession's design criteria are already based on meteorologic and hydrologic extremes that are continuously being revised (generally upwards, towards more extreme events) as new data are recorded. This has been the case with the National Weather Services' periodic upward revisions of the Probable Maximum Precipitation (PMP) that, in turn, engenders updates of the design floods for flood control structures. Thus, a case can be made that a good deal of the anticipated climatic variability for the near-term has already been taken into account for existing projects through the Corp's traditional, but highly reductionist and incremental approach to reliability analysis.

Another reason for the absence of a clear policy is that the Corps is reluctant and indeed, unable to use the relatively unrefined climate change predictions (especially on an intra-continental regional basis) as a justification for changing project design features or adjusting design standards. Furthermore, the Corps faces substantial difficulties in explaining and supporting those future probable events that comprise a climate change scenario as part of the series of forecasting activities that serve as the fundamental basis for evaluating alternative projects before a skeptical public influenced by stringent budgetary constraints. It may seem ironic that the very procedures which call for generating future scenarios and forecasts of population, economic growth, land use and ecological trends, often generate the most public controversy in water resources planning. The development of future scenarios called for by the U.S. Water Resources Councils' "Principles and Guidelines" (P&G; 1983), often hold the key to whether a water project is economically justified, as well as how large it should be.

Finally, a policy directed at anticipating changes of fifty years or more from now must take into account the reality of the effect that economic decision rules have on public investment choices. Although the Corps generally plans for a fifty year project life, the effective economic return on a water resources project is heavily influenced by the discount rate. The federal discount rate for water project economic analysis is nearly 9 percent, and is fixed by law. This means that most project benefits are realized within ten years, and the Corps' effective project evaluation and decision horizon is less then fifteen years.

In summary, global climate change implications for quantifying meteorologic and consequent hydrologic changes have not been developed well enough for use by practicing water resources engineers. The Corps of Engineers, as a consequence, is not in a position yet to develop a unified response to the threat of climate change and its water resources management implications. Nevertheless, the Corps has undertaken a series of changes and modest initiatives to some of the more important component parts of its planning, design and management responsibilities. First, both planning procedures and environmental impact statement guidelines call for the consideration of reasonably foreseeable future events as part of developing forecasting scenarios. Second, planning procedures require the development of alternative solutions to water resource problems that fulfill the forecasted needs in an economically efficient manner. The alternative solutions that are typically proposed consist of structural and nonstructural measures. These alternative measures undergo risk-cost analysis that could explicitly consider impacts of climatic uncertainty, both for magnitude and frequency of the hazard and for project benefits and costs. Non-structural measures include emergency warning and evacuation plans, water conservation measures, reallocation of water, trading and selling water rights, floodplain management and other non-traditional solutions.

Design standards also undergo risk analysis as part of structural project performance reliability analysis. Management of existing water resources projects calls for a systems analysis approach and changes in operating rules, supplemented decision-making drifts towards real-time operation. Traditionally the emphasis of Corps concerns has been on the high flow, flood control end of the hydrologic spectrum. Nevertheless, Corps flood control reservoir projects also provide a capability for dealing with low flows, increasing the robustness and resiliency of the entire operating system. These systemic properties should continue to be exploited as future demands shift under climate uncertainty, particularly in meeting future urban water needs.

PREVIOUS WORK

One can argue that the Corps has contended with the climate variability hypothesis, and its consequences, both in water resources management and in coastal shoreline protection since its assumption of those responsibilities. "Normal" low frequency and high frequency climate variability, without the superimposed consequences of global warming, have served as the basis for most project design. Some of the nation's best theoreticians helped the Corps develop and continually refine its current procedures and practices for design under climate uncertainty. For example, P. Bruun, who is often cited for his perceptive thinking on the coastal geomorphic consequences of sea level rise did some of his earliest work for the U.S. Army Corps of Engineers Beach Erosion Board in the mid-

1950's. Likewise, some of the earliest applications of stochastic hydrology and watershed modeling were performed under research initiated by the Corps of Engineers, the Soil Conservation Service, and the Bureau of Reclamation. The work of the Corps' Hydrologic Engineering Center (HEC) is known worldwide. The Corps' Institute for Water Resources (IWR) initiated a series of studies on climate change that paralleled an increased interest in global warming and its hydrologic consequences as part of the National Climate Program Act of 1978. IWR commissioned a series of studies to ascertain the hydrologic and geomorphologic impacts of climate change under four scenarios:

I	$+2^{\circ}$C, +10% precipitation
II	$+2^{\circ}$C, -10% precipitation
III	-2°C, +10% precipitation
IV	-2°C, -10% precipitation

Stockton and Boggess (1979) produced a comprehensive review of the hydrologic implications on each of the 18 hydrologic basins of the basins of the coterminous United States. Knox (1979) reviewed the possible geomorphologic consequences on each of the 18 river basins as well. Beard and Maristany (1979) discussed the potential changes from the vantage point of water resources engineering practices, while Fritts and Lofgren (1979) placed climate change scenarios within the context of periodic shifts in climate patterns during the pst 300 years based on tree rings studies.

ENGINEERING RISK AND RELIABILITY ANALYSIS

There have been other studies on the same theme, using different approaches and a variety of sophisticated models that are very well summarized by V. Klemes (1985) and M. Beran (1986). The key point is that the Corps and other operating water resources agencies have been aware of the scientific progress in climate change modeling and about the debate that has ensued with respect to the likelihood of predicted outcomes. The Corps is also aware that many authors that have written on the climate-hydrologic linkages have lamented the fact that the necessary transformations between Global Circulation Models (GCM's) that are time - and space - averaged and the consequent climate and weather effects, that are prerequisites for better hydrologic prediction, are seriously lacking. As a consequence, hydrologists have had to work backwards in evaluating climate change consequences by constructing a set of plausible scenarios, based on GCM results without even being able to assign a reasonable set of probabilities to those scenarios. Thus, while global warming should, on a global scale, lead to a "warmer-drier" scenario, it is not at all certain that some areas of the North American continent will not be "cooler and wetter". We also do not know whether the variability of the extremes will increase or decrease, notwithstanding the Environmental Protection Agency's (1984) attempt to transpose global changes to regional runoff changes.

The absence of good information on consequences is especially troublesome for an operating agency such as the Corps that interacts closely with the public. The Corps plans and designs water resources management projects under intense public scrutiny and thus is held accountable for a large number of forecasting assumptions, among which include the selection of extreme events as design objectives, and of future water demands and of population growth. While other regulatory agencies and scientific organizations propose various conditions, regulations and constraints on a range of future human activities, the Corps must continuously justify them in terms of social acceptability, economic efficiency, financial feasibility, and engineering reliability at the project level.

This continuous public pressure has contributed to the development, over the course of 50 years of application and refinement, of a large body of empirical and theoretical procedures and decision rules that have yielded what are generally considered to be fairly robust and resilient project designs. The empirical design procedures are intrinsically related to climate variability. We think that this empirical approach, emphasizing as it does the extremes of climate variability over the past 100 years, encompasses a significant proportion of the anticipated changes, at least for large scale water management systems.

Fiering (1982) defined robustness as the sensitivity of key system design parameters to variability in future events. That is, a robust water resources system is able to absorb the inevitable range of uncertainties associated with the planning and design of a water resources management project. These include the typically cascading or cumulative uncertainties of model selection, parameters and data and what is sometimes termed "strategic" uncertainty - i.e., the forecasts of future conditions, needs and projects outputs. Resiliency is defined as the ability of a system to return quickly to its designed performance levels, even after failure (Fiering, 1976).

What makes the Corps confident that their current water management systems can absorb the anticipated near-term climate changes? Many of the Corps' critics contend that Corps projects are overdesigned. In some cases that is probably true. The Corps was trying to anticipate future needs without a firm basis in growth projections. In most instances, however, the design criteria merely reflected the conventional engineering approach of focusing on an extreme event or condition, e.g., the critical drought period of record or the probable maximum flood or hurricane. This approach accounted for the unknown climate variability and the uncertainty that the existing data did not reflect the true range of possible events.

As a counterweight, however, the Corps' complex economic efficiency-based evaluation rules that are superimposed over conventional engineering design procedures, drive both project selection and sizing towards an optimum in terms of the appropriate or efficient level of protection. For example, a flood control reservoir is first sized for the economically efficient level of flood protection, generally between a 100-year flood and a larger Standard Project Flood (SPF). But the dam spillway is sized separately for an even more extreme flood event, termed the Probable Maximum Flood (PMF) to prevent dam failure through overtopping. Each analysis undergoes a separate risk-cost evaluation, operating under different economic decision rules, to reflect the escalation in the consequences of failure from property losses to loss of life. Similarly, an levees have "freeboard" that compensate for uncertainty inherent extreme flood events. There have been many recorded instances in which dam spillways and levee freeboards have saved the populace from severe, unanticipated flooding events.

Matalas and Fiering (1977) concluded, and subsequently reinforced in a number of other papers on the subject, that "...it is comforting to recognize that most large systems contain so much buffering and redundancy that resilient design can be operationally achieved without resort to sophisticated or elaborate projections about the climate". Several other comparative studies have shown that there is little discernible statistical difference in hydrologic models that reflect a stationary climate hypothesis versus those of a non-stationary climate, at least for long-term changes of the mean in precipitation and runoff of less than 20% (Klemes, 1985). Thus, public water resources agencies have effectively been conducting the design of large hydraulic structures and water control systems almost as if anticipating climate change. The design of smaller structures, such as urban drainage culverts and sewers, and local flood protection projects are more susceptible to changes in the variability of events, however.

RISK-COST EFFECTIVENESS ANALYSIS

Society cannot afford to build "fail-safe" projects anymore. It isn't economically efficient, either for water supply, flood control, or hurricane storm protection on coastal shorelines. Notwithstanding the Corps' past history of a reliability-based analysis for extreme events, their design concept has increasingly become "safe-fail". It is a strategy of designing flood protection for less than the extreme event of record. A structural measure (levee, channel) is complemented by emergency management plans that mitigate the damages of designed (i.e. safe-fill) failure of structural solutions. In other words local flood protection could conceivably be designed for a 20 to 50 year level of protection, as long as there is a complementary flood warning and evacuation plan. These complementary mechanisms represent an important contributing factor to the robustness and resiliency of water resources management systems, and are specially relevant to adaptation under climate uncertainty. The dichotomy between structural and non-structural measures also serves to emphasize functional and conceptual differences between risk assessment and prediction of climate consequences from that of risk management. While hydrologists may not be able to explicitly factor in the anticipated variability of climate change, especially if they rely on empirical rather than causal models, water resources planners and engineers can implement a wide range of management measures that increase the robustness and resiliency of solutions that can operate under an anticipated range of climate uncertainty. Adaptive risk management includes measures for floods and droughts.

Among the measures that are actively considered by water resources planners (including engineers, economists, social and environmental scientists) are the previously mentioned hazard mitigation measures that are employed when the hazard prevention measures (dams, levees, sea walls) fail. Also, many solutions address longer term and more permanent adjustments in the way which society uses its water resources. Changes in water pricing will redistribute the demand toward more efficient uses of water and will induce the various sectors (e.g., agriculture, municipal and industrial) to develop more efficient water using methods. Water can also be reallocated by changes in water laws and reservoir operating criteria. Water resources management is becoming more efficient and effective, with greater reliance on a range of water conservation measures and a systemic water resources operations approach. All these changes increase the buffering capacity of the existing systems, i.e., its robustness (ability to absorb surprises) and resiliency (ability to recover from failure).

ANTICIPATED WATER RESOURCES PROBLEMS

Notwithstanding this admittedly benign assessment of the near-term (10-20 years) ability of a regional water resources infrastructure to absorb most consequences of anticipated climate uncertainty, there are many user-specific and site-specific water resources needs that are currently stressed and where substantial shortfalls already exist. Little has been said also about the possible effects of climatic marginality (Wigley, 1985). This is the physical reality that under a climate change scenario, i.e. a shift in the mean, would also be accompanied by extreme events that may occur more frequently and where the frequency might change substantially even from a rather small change in the mean. Areas that are currently in marginally productive agricultural zones, would be most affected by the amplified cumulative impact of successive extremes (Wigley, 1985).

The Corp's (Stockton and Boggers, 1979) study of the sensitivity of 18 river basins to climate change focused on water shortages rather than on floods. Stockton's work showed that even today, several river basins are operating near the upper limit of their potential yield (Table 1).

TABLE 1

	Present Climatic State					Scenario 1 (warmer and drier)			Scenario 2 (cooler and wetter)		
Region	Estimated mean annual supply (bgd)[a]	Estimated mean annual requirement (bgd)[c]	requirement / supply	total storage / mean annual flow	Q_{05}/Q_{95} (streamflow)	Estimated mean annual supply (bgd)	total storage / mean annual flow	requirement[e] / supply	Estimated mean annual supply (bgd)	total storage / mean annual flow	requirement / supply
01. New England	78.6	1.03	0.01	0.38	2.2	56.6	0.54	0.02	108.5	0.28	0.009
02. Mid-Atlantic	81.0	3.54	0.04	0.48	2.4	53.5	0.73	0.07	115.0	0.34	0.03
03. South Atlantic Gulf	232.5	10.05	0.04	0.39	2.9	148.8	0.42	0.07	339.5	0.19	0.03
04. Great Lakes	75.3	4.69	0.06	0.27	2.3	50.5	0.41	0.09	103.2	0.20	0.04
05. Ohio	179.0[b]	4.33	0.02	0.29	2.4	111.0	0.47	0.04	256.0	0.21	0.02
06. Tennessee	41.1	1.11	0.03	0.75	1.9	25.9	1.20	0.04	56.7	0.55	0.02
07. Upper Mississippi	114.0[b]	2.66	0.02	0.27	2.9	70.7	0.51	0.04	166.4	0.18	0.02
08. Lower Mississippi	416.8[b]	5.51	0.01	0.05	3.7	291.8	0.09	0.02	571.0	0.03	0.009
09. Souris-Red-Rainy	6.1	0.47	0.07	1.72	1.4	3.4	3.11	0.14	10.2	1.03	0.05
10. Missouri	61.5	26.14	0.42	2.92	4.1	22.1	8.12	1.18	100.9	1.77	0.26
11. Arkansas-White-Red	67.7	12.03	0.18	1.32	5.5	31.1	2.41	0.39	138.8	0.66	0.09
12. Texas-Gulf	35.6	12.52	0.34	1.97	10.3	17.8	3.34	0.70	71.2	1.05	0.18
13. Rio Grande	5.3	4.80	0.87	3.58	22.0	1.3	14.2	3.69	9.5	1.99	0.51
14. Upper Colorado	13.9	11.79[d]	0.84	1.38	4.0	9.3	2.21	1.26	27.0	0.72	0.44
15. Lower Colorado	8.3[b]	9.87	1.18	12.66	1.4	3.6	18.99	2.74	14.1	4.83	0.70
16. Great Basin	13.9	4.37	0.31	0.51	3.8	7.6	0.93	0.57	25.3	0.29	0.17
17. Pacific Northwest	286.5	17.28	0.06	0.40	1.9	171.8	0.62	0.10	386.6	0.28	0.04
18. California	73.4	30.39	0.42	1.08	4.0	41.1	2.15	0.74	119.6	0.63	0.25

(a) assumes zero ground water overdraft
(b) inflow from upstream region included
(c) projected through the year 2000
(d) includes 6.70 bgd for downstream obligations
(e) assumes no increase in evapotranspiration rate from present climatic state

A warmer and drier climate scenario, which is the most likely for these arid areas, well only exacerbate the problems. Yet, flooding is still the most destructive and costly of natural disasters in the United States, accounting for average annual damages of $4.0 billion and nearly 250 fatalities (Schilling et. al, 1987). There are approximately 20,000 communities that have invested in some form of flood control or storm drainage systems. Unlike the redundancy built into the large scale mainstream water control structures, storm drainage systems are designed for more modest sized events, usually for storms between a 5-25 year recurrence.

Drainage, or stormwater management, is a companion to flood control, emphasizing the rapid removal of excess water. The cumulative investment in urban stormwater drainage is thought to exceed that of flood control projects according to a report on water resources by the National Council on Public Works Improvement (Schilling, et. al, 1987). In addition, the Public Works Improvement Council report provided an estimate of an additional investment of more than $100 billion that would be needed for constructing and rehabilitating combined stormwater sewers. The sizing of those facilities is very sensitive to storm frequency, seasonal distribution, and volume estimates. Thus, climate change impacts for this feature alone could have significant financial consequences, in addition to introducing considerable uncertainty into design reliability.

Because there is no clear picture of how the temporal and spatially-averaged global warming outcomes of the GCM models will affect continental and regional weather patterns, it is difficult for hydrologists to conduct direct sensitivity analysis on the hydrologic uncertainty. The present climatic-hydrologic uncertainty is not only one of magnitude, frequency, and variability, but also of direction. A "warmer-drier" scenario may well be the most likely consequence in the Midwest, forcing water resources planners to focus on drought and water supply shortages. Simultaneously, there may be "cooler-wetter" conditions in the Pacific northwest and southeastern United States, requiring a reevaluation of our flood-related design criteria, especially for the extensive levee-confined river reaches of the lower Mississippi valley.

CHANGES IN EVALUATION PROCEDURES AND ADAPTIVE MEASURES

A concerted effort needs to be made by academia and the Federal research laboratories dealing with hydrologic and hydraulic phenomena to provide information and techniques that are useful to engineering practitioners. Too much research in hydrology has been diverted to marginally relevant statistical and probabilistic empirical formulations that do not further the understanding of the underlying phenomena and their consequences. There is a serious debate within the hydrologic research community about the value of much of the research that is produced (e.g., Fiering, 1982; Klemes, 1986; Beran, 1986). This questioning of purpose has carried over into the even more complex area of hydrologic analysis under climate uncertainty.

The more pragmatic operating agency hydrologists would just as soon sit back and wait for the controversies to resolve themselves and for climate modelers to provide more site-specific and accurate information on precipitation magnitude and variability. The National Weather Service should play a major role in the transformation of global climate data to regional precipitation information. The sizing of water supply and flood control structures depends very much on the timing and distribution of runoff - whether it comes in a single season or as a double seasonal peak; whether the precipitation is monsoonal or evenly distributed; whether it comes as snowmelt or as storms. This is the level of information that the hydrologist needs from the climate modeler. We also need to begin using some of the better developed phenomenological or "causal" watershed models to better understand the sensitivity of various river basins to climate change. Some work along these areas has already been done (Klemes, 1986; Gleick, 1987). Curve-fitting alone will not do the job as we began to prepare for the consequences of climate change twenty or more years from now.

We also need a complementary review of water resources evaluation principles and procedures. A formal and uniformly structured approach to risk analysis would comprise one set of evaluation principles that would assist in decisionmaking under uncertainty. Formulation of alternative solutions that are more robust and resilient would be one of the desired outcomes of risk sensitivity analysis. However, these solutions are often "second best" in terms of economic efficiency criteria, so explicit risk-cost tradeoffs must be allowed to become part of the water resources evaluation procedures, rather than a strict adherence to the maximization of net benefits criterion as directed in the "Principles and Guidelines" for water resources planning and evaluation. This is true both for beach protection projects, that are under the double threat of sea level rise and variability of extreme events, as well as for water resources management systems.

More effort must be put into the prevention of the causes of climate change. This is a man-made phenomenon that can be controlled to some extent in a fairly cost-effective manner. A good start has been made by the recent international treaty on the control of the causes of ozone depletion. There is an inertia in the atmosphere-ocean system that will, in any event, still drive the specific climate-weather adjustments to significantly affect weather variability and the extremes of floods and droughts for some time to come, even after complete control of the agents of warming.

If little can be done to reduce or decelerate the causes of climate change, then society will have to consider larger structural changes, depending on how severe the climate-induced water resources consequences will be. We may have to consider relocating large segments of the population from the flood plains, coastal areas, and arid areas. A large scale economic adjustment will likely take place both in the composition of agricultural products and in the geographic distribution of agricultural areas. This will put additional, and possibly severe pressure on the dwindling natural ecological resources, particularly the prairie pothole wetlands and bottomland hardwood forests of the lower Mississippi valley. Winter navigation in the Great Lakes and many of the major rivers would be affected, possibly increasing costs of transporting goods, either because the waterways would be: frozen over longer periods; in flood stage more frequently; in low flow stages that constrain navigability.

Certainly more effort needs to be invested in climate modeling and the quantification of the climate-meteorology-hydrology linkages. Special attention should be given to the anticipated joint phenomeua of increased weather variability; greater frequency of extremes; and the potentially disastrous consequences of successive extremes. This is, perhaps more critical for droughts, as urban areas have grown rapidly in the past two decades, and depend on fairly rapidly exhaustible water supply sources. Drought planning and management is an important complementary action towards a complete risk management approach under climate uncertainty.

References

Beard, L. and A. Maristany, 1979. Hydrologic Effects of Climate Change. Prepared for U.S. Army Institute for Water Resources. Unpublished Draft Report.

Beran, M., 1986. The Water Resources Impact of Future Climate Change and Variability. In: J.G. Titus (ed.), Effects of Changes in Stratospheric Ozone and Global Climate, Vol I. Environmental Protection Agency.

Fiering, M., 1976. Reservoir Planning and Operation. In: H.W. Shen (ed.),Stochastic Approaches to Water Resources, Vol 2, Chapter 17, Water Resources Publications, Fort Collins, CO.

Fiering, M., 1982. Estimating Resilience by canonical analysis. Water Resources Research, 18(1) 51-57.

Fiering, M., 1982. Scientific Basis of Water Resource Management. National Research Council, Geophysical Research Board, National Academy of Sciences.

Fritts, H. and G. Lofgren, 1978. Patterns of Climatic Change Revealed through Dendroclimatology. Prepared for U. S. Army Institute for Water Resources, Unpublished Draft Report.

Gleick, P., 1987. The Development and Testing of a Water Balance Model for Climate Impact Assessment: Modeling the Sacramento Basin. Water Resources Research. 23(b) 1049-1061.

Klemes, V., 1985. Sensitivity of Water Resource Systems to Climate Variations. World Climate Program, WCP-98, World Meteorological Organization.

Knox, J., 1979. Hydrogeomorphic Implications of Climatic Change. Prepared for U.S. Army Institute for Water Resources, Unpublished Draft Report.

Matalas, N. and M. Fiering, 1977. Water Resource Systems Planning In: *Climate, Climatic Change, and Water Supply*. National Research Council, Geophysical Research Board, National Academy of Sciences, Washington, D.C. 99-110.

Schilling, K. and others, 1987. The Nations Public Works: Report on Water Resources. National Council on Public Works Improvement.

Stockton, C. and Boggess, 1979. Geohydrological Implications of Climate Change on Water Resources Development. Prepared for the U.S. Army Institute for Water Resources. Fort Belvoir, VA. Unpublished Draft Report.

U.S. Environmental Protection Agency, 1984. Potential Climate Impacts of Increasing Atmosphere CO_2 with Emphasis on Water Availability and Hydrology in the United States. Washington, D.C.

U.S. Water Resources Council, 1983. Economic and Environmental Principles and Guidelines for Water and Related and Resources Implementation Studies. U.S. Government Printing Office. Washington, D.C.

Wigley, T.M.L. 1985, Extreme Events, Nature, v. 316, 106-107.

OPPORTUNITIES AND LIMITATIONS ASSOCIATED WITH USING THE CONSERVATION RESERVE PROGRAM (CRP)

(By Jeffrey A. Zinn) [1]

Proponents of the view that there is a global warming problem are identifying approaches and seeking Federal program opportunities to address their concerns. One approach that has received considerable attention is to plant trees over millions of acres to sequester carbon dioxide. An opportunity to implement this approach may already be available through the Conservation Reserve Program. The CRP, a program that has been widely supported in the farm and environmental communities since its inception in 1986, provides both cost-sharing assistance to farmers to establish grasses or trees where crops had previously been grown on highly erodible land, and annual rental payments for 10 years to ensure that those plantings will be maintained. However, several potential impediments must be addressed before this program can be redirected from a cropland program with a minor tree-growing element to a significant force in sequestering carbon dioxide.

The first section reviews components of the CRP program that are relevant to an enhanced tree-planting effort. The second section looks at what CO_2 reductions could be bought with a modified CRP program, and at tradeoffs involved in changing the CRP from a focus on erosion control to a focus on tree-farming. The final section looks at some of the questions that remain if the program were to be modified to become a large-scale tree farming program.

THE CRP

The CRP, enacted in the 1985 farm act, is a voluntary program that allows farmers to bid to enroll highly erodible land into the reserve for up to 10 years. In return for enrolling his land, a farmer receives annual rental payments and also cost-sharing to assist in the planting of conserving vegetation. The program goal is to enroll between 40 and 45 million acres over 5 years, and "to the extent practicable," at least one eighth of these acres are to be planted in trees.[2] After seven bidding periods, or signups, the U. S. Department of Agriculture (USDA) has accepted bids on almost 28 million acres, including 1.76 million acres of trees. Tree acreage has been well below the program goals, and modifications to the regulations were made before the sixth signup to attract more tree acreage. Participating tree acres are concentrated in the Southeast; the three states with the most tree acres, Georgia (524,000 acres), Mississippi (326,000 acres), and Alabama (245,000 acres), account for more than 60 percent of the total.

The program is expensive—appropriations to support the program in FY 1989 are estimated to be $1.76 billion in the Reagan budget submission for FY 1990. These costs will be offset by savings from reduced production of surplus crops that the Government may have been forced to buy. Costs of the reserve could be further offset if the reserve grows large enough to reduce surpluses of commodities, resulting in higher market prices and lower Government costs for acquiring surpluses. In 1988, the American Farmland Trust, a program supporter, estimated that the program would be saving the Government several billion dollars, while USDA analysts estimated the costs would still exceed savings by several billion dollars.

---

[1] Specialist in Natural Resources Policy, Environment and Natural Resources Policy Division, Congressional Research Service, U.S. Library of Congress.

[2] Food Security Act of 1985, Act of Dec. 23, 1985. P.L. 99-198. 16 U.S.C. 3832.

Four components of the CRP program are particularly important to any consideration of reorienting it to a tree plantation program. First, the law allows rental agreements of 10 to 15 years; the Department has chosen to make all agreements 10 years so as to minimize Federal costs. This is 10 growing seasons for annual crops, but it is only a portion of one growing cycle for trees, and if trees are to be emphasized, a longer contract period may be more appropriate. If the contract is not lengthened, other incentives may be needed to ensure that participating acres stay in trees long after the rental payments have ended.

Second, participation in this program is voluntary. So far, the program has attracted the most participation in areas suffering from wind erosion in the arid West, where land values and production levels are relatively low, and returns from participating in Federal farm programs are also relatively low. In these areas, program costs are also less; that is farmers are willing to receive smaller payments to participate. Participation has languished in the East, where land values and returns from participating in farm programs are higher; but, the East is where trees can be most efficiently grown. If trees were to receive greater emphasis, program costs would rise. If most of these tree acres were in the Northeast or the Southeast, it is likely that offsetting savings from reduced commodity program outlays would also decline.

Third, eligible acres, under current CRP criteria, are concentrated in States between the Rocky Mountains and the Mississippi River, with the following States having more than 5 million eligible acres: Texas (13.9 million), Montana (8.6 million), Kansas (7.0 million), Colorado (5.5 million), Missouri (5.2 million acres), and Nebraska (5.0 million acres). Only one other State, Illinois, has more than 3 million eligible acres. In general, these States do not have large expanses of trees, and the potential for large forested areas is lower. Eligible acres are also limited, at a county level, to 25 percent the total cropland. This limit has been reached in nearly 100 counties, mainly in the States with the greatest signup.

Fourth, participants may leave the program at any time by paying back all the Government's expenses plus a penalty. In 1989, after the drought of last year and the increase in commodity prices, there is wide-spread speculation that many of the producers who joined the program recently (and would have little to repay) will drop out. These producers may believe that they can make more by farming than by idling their land. This speculation can not be confirmed at this time by agency officials who follow the program. However, this voluntary quality may be a concern because participation does not insure that the land will not be taken out of tree production whenever market forces indicate a better return from other uses.

POTENTIAL ACCOMPLISHMENTS OF A REORIENTED CRP

What would a reorientation of the CRP buy in terms of sequestering CO_2? Daniel Dudek of the Environmental Defense Fund prepared one scenario, which was offered as testimony last fall at several hearings on the global warming problems.[3] He concluded that the increased CO_2 emissions from the 86 power plants proposed for construction between 1987 and 1996 could be offset by planting approximately 10 million acres of trees. These 48 coal-fired and 38 oil-fired power plants would release 260 million metric tons of CO_2, according to the North American Electric Reliability Council. The 10 million acres of trees would sequester approximately 3 percent of the domestic CO_2 output, according to Dudek. (To place this relatively modest proposal in context, sequestering 5 gigatons of CO_2 per year from the atmosphere, an amount equal to current annual additions of CO_2 worldwide, would require between 1.28 and 1.65 billion acres of new plantation forests. By contrast, the total land area of the U.S. is little more than 2 billion acres.) [4]

The effectiveness of any tree-planting program will depend on the uptake per acre, the ability to keep sequestered CO_2 from returning to the atmosphere at a latter date, and many site-specific variables, including rainfall, soil characteristics and soil moisture, and silvaculture practices. Intensive management of tree plantings, also known as plantation management can raise the productivity per acre several times above growth rates found in natural or unmanaged stands.[5] Also, if the global warming process is, in fact, starting to occur, a host of new variables must be considered, including the effects of warmer temperatures on CO_2 uptake, changes in rainfall patterns, and, more broadly, changes in habitat that both foster and inhibit growth of tree species in various locations.

The uptake per acre will be determined in large part, by the specie of tree that is planted. Dudek discusses the relative ability of four tree species to take up CO_2—silver maple, black locust, American sycamore, and eucalyptus.[6] He estimates that sequestoring the emissions of the 86 new power plants would require at total of 11.11 million acres of silver maples, the least efficient of the four, or only 7.421 million acres of eucalyptus, the most efficient. All four tree species grow best in the more humid eastern United States. Other trees are also being looked at in other parts of the country; Douglas fir is being examined for its potential by scientists at the Bonneville Power Administration for example.[7]

---

[3] Daniel Dudek. Offsetting New CO_2 Emissions. New York, Environmental Defense Fund. September, 1988. 19 p.

[4] Gregg Marland. The Prospect of Solving the CO_2 Problem through Global Reforestation. Tennessee, Oak Ridge Associated Universities, Institute for Energy Analysis. Feb., 1988. 66 p. "DOE/NBB-0082"

[5] In a 1983 article in *Science*, "Biotechnology of Forest Yield", P. Farum and his colleagues made projections of productivity increases attributable to plantation management for Douglas fir in Washington and loblolly pine in North Carolina. For the Douglas fir, the natural yield of 5.7 tons per hectare per year can be increased to 8.8 with nitrogen fertilization, while for loblolly pine, yield can be increased from 3.6 to 11.8 with fertilization. Site and stand characteristics can cause these results to vary widely.

[6] The Forest Service has compiled data on the trees planted as a result of the first through sixth signups which has been recorded in the Agricultural and Conservation Stabilization Service's (ASCS) data base. (ASCS administers the CRP program.) This data set included almost 494,000 acres when it was run on December 14, 1988. Almost 75 percent of these acres are planted in loblolly pine. Of the four tree species identified by Dudek, less than 100 acres are planted in black locust and silver maple, and no acres are planted in the other two species.

CONSIDERATIONS IN REORIENTING THE CRP

If proposals to reorient the CRP were seriously considered, several variables would receive congressional attention. These include the political debate over tradeoffs between the benefits of taking the program in a new direction and the costs of redirecting it from its current soil erosion reduction goal, the Federal fiscal elements of a program reorientation (especially ways to offset potential increases in Federal outlays), and the effects of virtually permanently retiring a significant segment of agricultural land from production for longer time periods.

Criteria for accepting land into the CRP can be modified by the Department. Recently, for instance, qualifications for tree acres were reduced because enrollment of land to be planted to trees was less than lawmakers had hoped for. The Secretary of Agriculture could probably change the program further to attract more tree-acres because the Secretary has wide discretion. For example, he could lift the 25 percent enrollment cap in counties where the potential to plant trees was particularly high. In addition, the law states that lands may be included in the program "that are not highly erodible lands, but that pose an off-farm environmental threat", and one such threat could be CO_2 buildup.[8]

However, if the program were to be more heavily reoriented to trees, by adding the 10 million acres that Dudek calls for, as an example, congressional action might be necessary to ensure that the program retains its wide-spread political support. If a legislative proposal to change the eligibility criteria were made, a number of forces would likely enter the debate. The traditional soil conservationists would still want to see highly erodible land taken out of production. Environmentalists would want to be assured that the tree-acres would also protect other resource values, such as surface and groundwater quality. When those concerns are incorporated into a revised acreage equation, it may mean that less productive acreage would be eligible, requiring more land to meet the CO_2 goal. In summary, such a major program reorientation could probably be made only after the supporters of the current program could be assured that they are losing little of the benefits they either currently enjoy or are seeking.

During the 100th Congress, several bills were introduced that would expand the reserve from its current limit of 45 million acres to 60 million acres or more. These expansion proposals also included modifications to the program purposes. Such an expansion could absorb the tree-acre increase while retaining the other environmental values that the program promotes. However, views about whether such a program expansion is desirable is divided: major concerns are the additional Federal budget exposure and whether farmers would voluntarily bid that many acres out of production in light of current and anticipated market conditions; the strongest support comes from those who believe that additional environmental benefits can be bought with farmer support.

---

[7] Personal communication with Shep Buchanan, Bonneville Power Administration. January 1989.

[8] Food Security Act of 1985, Act of Dec. 23, 1985. P.L. 99-198. 16 U.S.C. 3831.

During any debate to expand or reorient the program, a focus of debate will be the cost. If the expanded program were to continue to operate as it has, with up to 50 percent Federal financing for the cost-share to establish trees and for 10 years of rental payments, costs to the government could be high. One possible solution is to require the utilities benefitting from the tree farm program to pick up either a portion or all of the costs for these acres. These costs would exist for the operating life of each powerplant. Dudek estimated that establishing the trees would average $150 per acre for planting a forest that is to be intensively managed. (By contrast, the Federal cost-share to establish trees on land in the CRP has averaged $40.00 per acre.) Annual rental payments for additional tree acres (9.26 million acres in his scenario) would be $926 million per year. If these payments would continue for the life of the plant, they would add an estimated 0.67 cents per kilowatt hour to costs of providing power from these plants, according to Dudek. If utilities picked up the entire cost, including establishment, their costs would rise. The cost would range from $1.26 to $1.34 per metric ton of CO_2 if the companies paid all the costs of the program, while if the utilities picked up the Government contract after the first 10 years, the cost per metric ton of CO_2 reduction would range from $0.67 to $0.73.

This proposal could include several variations, including having the utilities share in the Government costs during the first 10 years, and paying a bonus on top of Federal rental payments to participants. The contracts could be required for a set number of years based on the value of the trees rather than on the life of the power plant. One issue that would have to be addressed is the voluntary nature of the current program. For the revised program to succeed, either more acres would have to be planted to offset the anticipated portion of producers who might later decide to get out of tree growing, or the voluntary aspect of the program would have to be ended for producers who plant to reduce CO_2.

After a policy to grow trees to remove CO_2 has been set, there are still many questions that would need to be addressed. Trees grow at different rates, and their ability to sequester CO_2 varies both by specie and age. An intensively managed forest consumes energy, and the production of at least some of that energy will produce additional CO_2. Gregg Marland, a scientist at Oak Ridge National Laboratory, has estimated that the energy required to intensively manage a forest will be about 12 percent of the energy produced.[9] Finally, there are unknowns that will affect trees generally, such as the impact of acid precipitation.

If these lands were placed permanently into trees, the land would not be available for future agricultural production. During the 1980s, agricultural policy makers have pushed ahead, seeking ways to get more land out of production, and annual and long-term land-retirements, combined, have grown from 0 in 1980 to more than 70 million acres in 1988, more than 15 percent of the country's cropland. However, the recent drought, coupled with production shortfalls in other parts of the world, has raised both market prices and the specter of future world shortages. As market prices climb in response to shortages, the cost, whether it is the responsibility of government or a utility company to take land out of production, also will grow. Some agricultural analysts are starting to say that we need to retain most of the remaining potential cropland in a flexible reserve that is available to counteract production shortfalls. Others worry, however, that all the land in the conservation reserve could begin to come back into production agriculture in the mid 1990's, depressing markets, if additional actions are not taken.

---

[9] Gregg Marland. The Role of U.S. Forestry in Addressing the CO_2 Greenhouse Problem. Testimony to the Senate Committee on Energy and Natural Resources. Sept. 19, 1988. p. 3.

CONCLUSIONS

The CRP offers an existing opportunity to plant trees and take a small portion of the Nation's contribution of carbon dioxide out of the atmosphere. Whether the program can or should be modified to accommodate the Dudek proposal, or other similar ideas, is largely a political decision. Before Congress agrees to such a revision, however, it will have to debate many factors, including the costs of the program, the role of utility companies, other environmental values that the revised program might serve, and whether the program can continue to be voluntary for acres planted in trees to reduce carbon dioxide concentrations.

○